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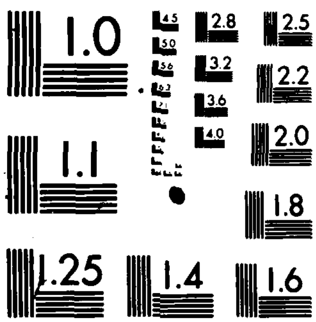
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ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

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AGARD ADVISORY REPORT No. 174

Windtunnel Capability Related to Test Sections, Cryogenics, and Computer-Windtunnel Integration

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AGARD Advisory Report No.174

WINDTUNNEL CAPABILITY
RELATED TO TEST SECTIONS, CRYOGENICS, AND COMPUTER-WINDTUNNEL INTEGRATION

by

The Windtunnel Testing Techniques Sub-Committee
of the
Fluid Dynamics Panel

This Advisory Report was prepared for the Fluid Dynamics Panel of AGARD.

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SUMMARY

This report is written by the Windtunnel Testing Techniques (TES)* Sub-Committee of the AGARD Fluid Dynamics Panel. Three areas of testing techniques are dealt with. In each of these three areas the TES Sub-Committee appointed two conveners, one from each side of the Atlantic. Through the auspices of AGARD these conveners brought together the foremost workers in each of the areas. The conveners and workers in these areas of work discussed what needs to be done, how the work should proceed and how it might be shared. One hundred and forty-nine leading research workers from the NATO countries participated in this work of the TES Sub-Committee and made valuable contributions. The three reports provided by the conveners form the main content of this document and are given in the Appendices 1 through 3.

Part 1 of this report describes the work undertaken and gives the rationale for the effort. Part 2 presents a commentary discussion of the three conveners reports and mentions applications of the technology as well as possibilities for coupling technology being obtained in more than one of the areas. Part 3 gives the implications drawn by the Sub-Committee from the conclusions and recommendations of the conveners reports as well as from Part 2.

Application of the technology discussed in this report can afford large improvements in windtunnel capability and effectiveness. Some of the technology discussed can be found in the literature as indicated by the references. Some of the technology appears here for the first time. The consolidated presentation of most of the pertinent work in each of the three areas as well as the discussion of serendipitous coupling between the work in two or more of the areas is unique to this report.

* TES – Techniques d'Essais en Soufflerles (French equivalent of Windtunnel Testing Techniques)

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WINDTUNNEL CAPABILITY RELATED TO TEST SECTIONS, CRYOGENICS, AND COMPUTER-WINDTUNNEL INTEGRATION

by

R.O. Dietz
Route 1
Manchester, Tennessee 37355, USA

PART I

INTRODUCTION

Experiments in windtunnels have been the major basis for improved understanding of fluid dynamics through research and for enhanced aerospace vehicle efficiency through development since before the first powered flights. The area rule concept, the supercritical airfoil, and engine installation configurations that provide favorable interference which are presently being applied to military aircraft and fuel efficient transport aircraft were evolved through windtunnel experiments. Present windtunnel experiments on active control systems and more complete integration of the propulsion system into the aerodynamics of flight vehicles will yield the improvements in effectiveness for the next generation of aircraft. Confidence that windtunnels are expected to continue to contribute to such advances is evidenced by the construction of the new large subsonic tunnel capabilities in Europe and in America, the construction of the cryogenic National Transonic Facility in America, and the planning for the European Transonic Windtunnel.

During the past decade greater and greater contributions to understanding of fluid dynamics and to the design of more efficient aircraft have been made by computational fluid dynamics or CFD. CFD is taken to be the solution of the established equations of motion of fluids through the use of well conceived algorithms and high speed computers with large fast-access data storage capability. Agardograph 241 entitled "A COMPARISON OF PANEL METHODS FOR SUBSONIC FLOW COMPUTATION" shows that for certain flight regimes CFD can be used to investigate a number of aircraft configurations over a broad range of flight conditions in a cost effective program to develop efficient multimission aircraft. One third of the papers in AGARD Conference Proceedings No.247 on "HIGH ANGLE OF ATTACK AERODYNAMICS" related to CFD work. This in a field where flow separation and reattachment, unsteady flows, vortex flows – – free and attached, are determining! NASA has preliminary designs in hand and is fostering construction of the National Aerodynamic Simulator which will be two orders of magnitude more capable than existing computers. Such a machine could effectively deal with the time dependent Navier-Stokes solutions for confined flow situations and with proper turbulence modeling could effectively deal with time averaged Navier-Stokes solutions for complete aircraft. Such a powerful CFD capability combined with the enhanced windtunnel capability being built in Europe and America are the essential tools for NATO aircraft superiority in the nineteen nineties.

The complementary roles of CFD and windtunnels, and their growing interdependence is becoming universally recognized. Generation of turbulence models for use in CFD is dependent upon careful windtunnel experiments. Understanding of measured afterbody pressure distributions in separated flow regions has been obtained by calculation of the related flow field. Windtunnel tests are used to verify the performance at critical flight conditions of vehicle configurations where evolution and performance estimates over an extensive range of flight conditions were CFD derived. The list of examples showing the power of combined use of CFD and windtunnels in superior aircraft development grows rapidly.

The Sub-Committee on "WINDTUNNEL TESTING TECHNIQUES (TES)" of the AGARD Fluid Dynamics Panel formally recognized in 1978 that the complementary roles of CFD and windtunnels as well as the advent of greater windtunnel capability represented by the new tunnels being constructed made a number of tunnel characteristics and test techniques so important that international cooperation on them was warranted. Experiments to generate turbulence models for use in CFD, for example, require a tunnel with carefully documented flow quality. Mean pressure coefficient, velocity (magnitude and direction), and temperature as well as turbulence and noise intensity over a range of frequencies should be defined spatially and temporally through the volume that will directly influence the model for each of the tunnel operating conditions to be used in the experiments. In addition, the influence of environments imposed by the tunnel upon measurements of importance in the experiment must be understood. Incidentally, this report presents the relation between boundary layer transition Reynolds Number and acoustic loading that evolved from an American flight test program and an extensive European and American windtunnel test program that were completed in 1980. Another type of test encountered in the interactive role of CFD and windtunnels is the test to verify the full scale

flight performance determined by CFD. Such a test requires accurate data that yield reliable full scale flight performance predictions. Precise data that document performance differences of models with configuration changes may not be adequate for this purpose.

Such considerations led TES, with the support of the AGARD Fluid Dynamics Panel and the AGARD National Delegates, to establish in 1980 three conveners' groups on windtunnels and test techniques. These three conveners' groups deal with the following areas:

(a) Transonic Test Sections

(b) Cryogenic Testing Technology

(c) Integration of computers and windtunnel testing.

TES selected these three areas because a high level of activity is expected in them during the next few years, their importance has been heightened by the interdependence of CFD and windtunnels as well as the new windtunnel capability being built, and the Sub-Committee's knowledge of European and American research and development showed that advances in the three areas could be enhanced through international cooperation.

Each conveners' group is led by two outstanding engineering/scientific contributors in the field under consideration. One convener is European, the other is American (USA or Canada). Conveners' names and the number of workers at each meeting are given in Table I. Each convener has brought together on his side of the Atlantic the foremost workers in the field. The conveners' groups reviewed work under way, discussed what must be done in that field, how the work should proceed, and how the work might be shared among the laboratories of Europe and America. American conveners attended European meetings and European conveners attended American meetings so that the conveners' reports (Appendices 1–3) result from considerations on both sides of the Atlantic.

This conveners' activity has provided for 58 European and for 91 American working level experts in three areas of vital importance to NATO air supremacy of the future to discuss together the work that they are doing. Sharing approaches being used, ideas about relative importance of parameters, and concepts for future work will favorably affect the work of the experts that participated. Requirements and concepts for future work that they have set down in their reports provide guidance for other workers in the three fields and could inspire students to initiate a career in one of the areas. Research and development managers are urged to act upon such conveners' findings as: windtunnel flow quality and data accuracy capabilities must be more completely defined; a standard calibration set of measurements and data reduction method for windtunnel flow quality definition would be useful; and test section boundary measurements for wall interference evaluation should be standard practice.

The basic content of this report is in the three appendices which are the three conveners' reports. Following this introduction is (a) a commentary discussion of the three reports by TES, and (b) the TES view of the implications of the main conclusions and recommendations of the three conveners' reports.

TABLE I

AGARD – FDP – TES CONVENERS' GROUPS AREAS, CONVENERS, AND NUMBER OF WORKERS
AT
1980–81 MEETINGS

AREA	CONVENERS	NUMBER OF WORKERS	
TRANSONIC TEST SECTIONS	Mr T.Binion, USA	America	11
	Mr J.P.Chevallier, France	Europe	10
CRYOGENIC TESTING TECHNOLOGY	Mr L.W.McKinney, USA	America	25
	Mr R.J.North, UK	Europe	12
INTEGRATION OF COMPUTERS AND WINDTUNNEL TESTING	Dr J.L.Potter, USA	America	55
	Mr M.C.P.Firmin, UK	Europe	36

PART II

COMMENTARY DISCUSSION

1. TRANSONIC TEST SECTIONS

The level of effort in this area is indicated by 37 references of the conveners' report, 30 of which were written during the past 3 years. Work in this area is well distributed with 5 organizations in the USA, the NAE of Canada, ONERA of France, 2 organizations in Germany, 3 organizations in the UK, the NLR of the Netherlands, and the FFA of Sweden being involved. The importance of a combination of mathematical and experimental investigation is appreciated at all 14 locations. There are numerous approaches to improved transonic test section design including compliant solid walls, variable geometry slotted, rod, and porous walls, as well as suction and blowing combined with the vented walls. Common to these approaches are needs for investigations of boundary conditions, instrumentation, external flow field calculations, wall interference assessment and correction methods, and minimization of test section turbulence and noise. Considering the half dozen approaches and the half dozen investigations that need to be tailored somewhat to each approach, it is clear that the 14 teams at work will be fully occupied during the next few years.

TES is satisfied that the current level of effort being invested by the 14 teams is well justified. Evolution of an adaptive wall test section that minimizes wall interference, turbulence, and noise while providing uniform pressure and velocity distribution will reduce considerably windtunnel time and cost for a new aircraft. The fourteen teams are kept informed of each others work and plans through TES and there is no unnecessary duplication of effort. The half dozen approaches along with some variations on them are all under investigation. There is not at present a sound basis for selecting one approach over the others and it is possible that one approach may prove to be the best for research in connection with turbulence modeling for CFD, for example, while another approach may prove to be best for performance verification tests of aircraft models. TES is confident that use of the techniques being developed in the program discussed in the conveners' report will become widespread during the coming decade.

Most of the work discussed by the conveners is devoted to adaptive wall research. There are a few tunnels of around one meter plus test section dimensions in Europe and in America that have variable area vents installed. Adaptive wall concepts could be partially implemented in such tunnels. The conveners' report discusses the success achieved with such application in the four foot transonic tunnel at AEDC. There are additional possibilities for application of the adaptive wall work to existing windtunnels. Installation of screens or rod wall liners to reduce test section noise; measurement of flow angle and static pressure near the existing tunnel walls with subsequent assessment and correction of wall interference using calculation methods generated in this program; and better definition of boundary conditions established by existing test section walls using the improved methods of calculating cross-flow characteristics of ventilated walls being developed in this program, represent useful examples.

Work described in the conveners' report gives several reasons for optimism and shows a couple of problem areas. The task of characterizing the cross-flow properties of ventilated test section walls under the influence of Mach number variations, model induced pressure gradients, and changing boundary layer thickness still appears formidable. On the other hand, in a solid compliant wall test with the supersonic region reaching both the upper and lower walls, the expected reflection of the terminal shock did not occur; and in a test at AEDC the wall pressure distribution between the correct upstream value, the correct minimum, and the correct downstream pressure was not critical to achieving the equivalent of unconfined flow. TES consideration of the results being achieved leads to the conclusion that any new tunnel design initiated at this time should incorporate as much adaptive wall geometry in the test section design as possible. Consultation with the experts listed in the conveners' report should allow selection of a wall configuration based upon the intended use of the tunnel. Even if instrumentation, mechanization, and the related computational capability cannot be initially installed, such equipment can readily be added. In the meantime, the adaptive wall geometry could be used at least in place of special tunnel modifications such as that presently being done in the eight foot pressure tunnel at NASA Langley.

2. CRYOGENIC TESTING TECHNOLOGY

The conveners' report makes clear, as proponents pointed out almost a decade ago, that the technical problems involved in cryogenic windtunnel testing are different, but not entirely new. Instrumented models under the influence of thermal gradients at cryogenic temperatures have been successfully tested in space chambers. Highly loaded models have been tested in pressurized windtunnels. Extension of this background for development of highly loaded wind-tunnel models operating at cryogenic temperatures has brought to fore many and varied engineering challenges and

engineering responses or solutions are being obtained in a timely manner. The engineering solutions being obtained are legitimate ones in that they provide for a greatly enhanced test capability with safety and cost effectiveness.

A scientific question that has been under consideration is shown to have been satisfactorily resolved by studies discussed in the conveners' report. Real gas effects on the various types of basic fluid dynamic flow situations have been theoretically investigated by NASA with the cooperation of the National Bureau of Standards in America. Analytical studies have likewise been made in Europe. Experimental investigations of real gas effect have been made in flow channels in both Europe and in America and with aircraft models in America. It has been satisfactorily shown that research and development data without compromise due to real gas effect will be obtainable in pressurized cryogenic transonic windtunnels.

The many engineering studies under way on models, test techniques and instrumentation for high Reynolds number cryogenic windtunnels are summarized in the conveners' report. TES considers the program quite comprehensive, and if a surprise is encountered in the operation of cryogenic windtunnels, it will be a surprise indeed. Consideration is being given to, and successful results are being achieved with regard to

Model design analysis

Model shape tolerances

Surface finish requirements

Effects of pressure orifices on data

Selection of materials

Force, pressure, temperature, model attitude and deflection measurements

Flow diagnostics in the form of laser Doppler velocimetry

Remote control manipulators for model changes between tests.

The conveners' report shows that positive results are being achieved on a time scale that corresponds to construction schedules for the new cryogenic tunnel that will operate in 1982.

The practicality of designing transport and fighter aircraft models for tests in pressurized cryogenic windtunnels has been raised as an issue many times since the new high Reynolds windtunnels have been under consideration. This conveners' report shows that aerodynamic loading on models of transport aircraft presently used in conventional tunnels will provide for testing transports which are the size of the L-1011 airplane at flight Reynolds numbers in the cryogenic environment. Tests of models of the larger B-747 type aircraft at flight Reynolds numbers in a cryogenic tunnel dictate that models be designed for $C_L q$ only 50 percent greater than for currently used models. The report shows that likewise for fighter models which achieve maximum allowable g-loading at altitudes corresponding to 12,000 meters, the model can be tested in a cryogenic windtunnel at the same g-loading at Reynolds numbers corresponding to 3,000 meters altitude. The conveners' report on "INTEGRATION OF COMPUTERS AND WINDTUNNEL TESTING" discusses the advantages of a combined use of computer simulation and windtunnel simulation to produce data at or near trim flight conditions, thus avoiding the necessity for matrix testing at all attitudes at all Mach numbers and Reynolds numbers. Combined consideration of such a test technique along with the model load discussion of this conveners' report leads to the conclusion that extensive use can be made of the high pressure capability of the new cryogenic windtunnels with $C_L q$ values used for current windtunnel models. It is clear that complete exploitation of the capability being provided in the new windtunnels will impose more stringent requirements on model design and for this reason safety factors will be decreased and more sophisticated engineering analysis and pre-test loading of models will be used. Capabilities for the improved analysis and structural tests of models are being developed.

TES's view is that the methods used by the NASA in preparing for testing in the National Transonic Facility in America is quite rational and warrants duplication by others undertaking similar enterprises. Extensive in-house engineering and research are being used to accumulate cryogenic testing technology. Studies contracted to universities and industries are being used as well. Workshops and symposia at needed frequency are used to obtain inputs from industry, universities, and other government agencies that formulate the technology program to be followed as well as to report back to the interested parties on the results that have been achieved.

There is a large difference in the character of the European and American programs on cryogenic testing technology. NASA has been operating a 0.3 meter cryogenic research tunnel for eight years. McDonnell-Douglas Corporation is converting a four foot by four foot tunnel into cryogenic operation. The NASA eight foot by eight foot National Transonic Facility is scheduled to become operational one year from now. France has placed into operation Tunnel T-2 which is a 40 x 40 cm cryogenic transonic tunnel. PETW, which is a 24 x 27 cm transonic cryogenic tunnel is being built for operation in 1982. Conversion to cryogenic operation of the 2.4 x 2.4 meter subsonic tunnel at Cologne is to be completed by 1983. Testing technology is being accumulated more rapidly and with greater urgency in the American program than is the case in Europe. However, the level of activity on both continents is high and there are normally scheduled meetings of experts in both Europe and America. The suggestion by the conveners that conveners' meetings be dispensed with is deemed appropriate and we recommend its implementation. Normally scheduled meetings on cryogenic technology in Europe and America will serve the purpose of the conveners' meetings. Auspices of AGARD

should be used to promote the presence of American representatives at the normally scheduled European meetings and the presence of European representatives at normally scheduled American meetings.

3. INTEGRATION OF COMPUTERS AND WINDTUNNEL TESTING

The attendance at this conveners' activity reflects the current high level of interest in this area. Fifty-five working level experts attended the meeting in America and there were thirty-six attendees at the European meeting. We note that attendees included computational fluid dynamic experts, windtunnel operators, and the specialized people who work on the integration of computers and windtunnels.

The report shows the application of high capacity digital computers and the development of sophisticated mathematical models for interaction with windtunnels. The different approaches used by the various tunnel operating groups in integrating windtunnels with computers gives credence to the conveners' conclusion that cooperative endeavors beyond a continuation of the exchange of ideas through the conveners' group would not be useful.

The demonstrated improvement in effectiveness and efficiency of the research and development process through integration of computers and windtunnels discussed in the report are impressive. Small models with flow-through nacelles under test in the windtunnel have had engine effects on steady state and transient flight conditions incorporated on line in real time by mathematical modeling. Such models have used analytical engine performance as well as experimentally determined engine performance. Thrust differences in twin engined aircraft which occur at high angles of yaw have been included in studies of aircraft departure from stable flight using this technique.

Significant savings in windtunnel time and cost have been achieved with on line modeling of the aircraft equations of motion to obtain data at or near trimmed flight conditions. Aircraft weight, center of gravity location, and engine thrust are inputs to the mathematical model that are combined with experimental aerodynamic coefficients to set trim attitude at specified altitudes and air speeds. The system yields the specific design information desired without the requirement to test the model over a complete matrix of Mach number, attitude and altitude for later extraction of trimmed flight data. The user has available to him at the conclusion of the test the design information which he seeks without extensive post test manipulation of the data. Windtunnel time savings of a factor of five have been achieved with the use of this type of integrated test technique in performance evaluation of a cruise missile configuration.

The conveners have, in our opinion, correctly noted that extrapolation of currently obtainable windtunnel data to flight conditions is difficult even with the best CFD techniques now available. They project that availability of data from the new high Reynolds number windtunnels will improve the situation markedly. TES believes that this is an accurate representation of the situation for extrapolation of windtunnel model data to flight.

The conveners' report makes the assertion that the application of high speed digital computers is inaugurating a revolution in the areas of wall interference and sting interference correction. On line assessment of and correction for such interference based on measured pressures and flow angles near the test section walls are rapidly becoming feasible. We commend to the windtunnel testing community the conveners' recommendation that windtunnel testing should include measurements of the wall boundary conditions as a standard practice. These advances and their implementation will be dealt with further at the Fluid Dynamics Panel Specialists' meeting on Wall Interference to be held in London in May, 1982.

The conveners' report calls attention to the requirements for high quality flow in windtunnels that are to generate data for the assessment of CFD codes. The need for tunnel calibration that documents pressure coefficient, velocity vector magnitude and direction, acoustic disturbances that is discussed in this report lends support for further work on determining data accuracy and flow quality requirements for windtunnels.

The conveners' report discusses numerous instances in which pretest generated CFD data are compared on line with experimental data to guide the windtunnel test program. This mode of operation has improved windtunnel productivity. On line generation of CFD performance prediction is not necessary for this mode of operation. The increase in cost of tunnel operating time and the time required for CFD performance prediction appears to preclude the operating mode where CFD and experimental data are generated simultaneously on line. Rapidly available CFD results would be useful to aid in the interpretation of model pressure distribution measurements which are unexpected so as to enhance the value of the data to the user. This type of CFD support to windtunnel testing can be accomplished with post test CFD.

We deem it important to include in this section additional concepts that relate to the conveners' work and discussion on the integration of computers and windtunnels. The enhancement of the research and development process offered by the integration of computers and windtunnels and the inter-dependence of CFD and windtunnels leads us to conclude that each major windtunnel facility should have in conjunction with it a major computational fluid dynamic capability. The CFD capability should include the most up to date and capable computing equipment, computer programmers, and engineer/scientists for development of mathematical models to contribute to the ongoing windtunnel-computer integration process. We observe that a windtunnel with an up-to-date computer capability can become practically a "back yard" facility to remote users. Aerodynamic coefficients computed on line from the experiment underway and

compared with pre-test generated CFD performance predictions can be displayed on a cathode ray tube in the wind-tunnel control room and on the user's computer console. The data links available with modern communication facilities provide for such display as well as for on line interraction between the user's console and the control room operator's console. This mode of operation has been successfully demonstrated between AEDC and Dayton, Ohio and between AEDC and Palm Beach, Florida. The mode of operation enhances the utilization of the large capital investments in windtunnels and other ground test facilities.

PART III

IMPLICATIONS OF THE RESULTS

The three conveners' reports which constitute the Appendices of this report each contain recommendations and conclusions. TES has reviewed those and considers them valid. This section gives our view of the implications of the work done by the conveners.

Application of the technology discussed herein offers large improvements in capability and effectiveness for existing and future windtunnels. Principally new methods for minimizing wall interference and correcting for wall interference, model design and fabrication techniques, instrumentation techniques and better definition of the flow environment provided in a windtunnel will provide higher quality data and significantly reduce time and cost for windtunnel testing in aircraft research and development. The integration of computers with windtunnels provides types of data hitherto unavailable, reduces testing time, and diminishes the requirement for post-test analysis by the user.

Material discussed in the conveners' reports shows that measurement of boundary conditions should be made in most current windtunnel tests. Such measurements should be used for assessment of wall interference and its correction where feasible.

Modification of the four foot tunnel to cryogenic capability by McDonnell-Douglas, construction of a cryogenic transonic tunnel by NASA and proposed construction of a cryogenic transonic tunnel in Europe are proving to be prudent decisions. Model design, instrumentation and testing technique technology are being developed in a timely manner. Progress achieved that is reported herein is uniformly encouraging, and confidence is being gained that realization of the full potential of these tunnels will not be compromised by the lack of such technology.

Modern computer capability, properly supported with programmers and engineers, can be used to conduct windtunnel tests at or near trim flight conditions and through maneuvering flight to departure. Such capability can be used for CFD that will aid in interpretation of experimental results. It can be used to present aerodynamic coefficients on line during windtunnel tests and compare them, on line, with other experiments and analytical predictions. High data rate linkages between computers located far from one another that is afforded by modern communications systems can make each windtunnel a "back yard" facility for aeronautical designers and researchers at companies and universities far from the windtunnel. On line data are transmitted from the windtunnel computer to the computer at the user's installation. User inputs regarding the test program can be provided on line via computer communications in the reverse direction. This concept has been tried with success by connections between AEDC and Ohio and between AEDC and Florida. The National Transonic Facility at NASA Langley includes equipment for the concept.

Existing windtunnels and the new windtunnels should be calibrated more thoroughly than has been the practice in the past. The data are needed as evidenced by the report of Working Group 04. The data can be obtained as evidenced by the conveners' report on TRANSONIC TEST SECTIONS. This conveners' report indicates as well the type of calibration data required. The increasing capability of computational fluid dynamics and of windtunnels discussed in this report makes evident the importance of the work of a fourth TES conveners' group whose work is not discussed in this report. That conveners' group has been assigned the task of defining data accuracy and flow quality requirements for windtunnels that are implied by the use of the windtunnel to support CFD, validate CFD results, and to contribute most effectively to experimental fluid dynamics research and development. The work done thus far by the conveners' group on data accuracy and flow quality requirements represents a valuable beginning. The work should be pursued further.

Two of the conveners' groups whose work is discussed in this report should be continued during the coming two to three years' time cycle. The conveners' groups on CRYOGENIC TESTING TECHNOLOGY should be discontinued. In place of the conveners' groups on CRYOGENIC TESTING TECHNOLOGY, auspices of AGARD should be used to promote presence of American experts at normally scheduled meetings of European cryogenic workers and presence of European experts at normally scheduled meetings of American cryogenic workers.

The Fluid Dynamics Panel of AGARD should consider a specialists' meeting on cryogenic testing technology for late 1983 or 1984.

APPENDIX 1

REPORT OF THE CONVENERS GROUP ON TRANSONIC TEST SECTIONS*

by

T.W.Binion, Jr
Calspan Field Services, Inc.
Arnold Air Force Station, Tennessee 37389

and

J.P.Chevallier
Office National d'Etudes et de
Recherches Aerospatiales, Châtillon, France

Edited by
M.L.Laster
Arnold Engineering Development Center
Arnold Air Force Station, Tennessee 37389

I. INTRODUCTION

Under the auspices of the AGARD Fluid Dynamics Panel Subcommittee on Wind Tunnel Test Techniques, two convener meetings were held with various experts concerned with developments of transonic test sections. Experts from the USA and Canada met on March 13-14, 1980 at NASA Langley, Hampton, Virginia, and the European experts met May 8-9, 1980, at the Hochschule der Bundeswehr, Munich-Neubiberg, Germany.

The meetings were concerned with discussions of the research activities affecting the development of improvements to transonic test sections accomplished since the information in Appendix 6 of Ref. 1 was compiled. A summary of current and planned research and recommendations from the two groups is presented herein.

II. CURRENT AND PLANNED RESEARCH

2.1 THEORETICAL STUDIES

D. L. Dwoyer, NASA-Langley, is using a vorticity stream function formulation of the time-dependent, incompressible, two-dimensional Navier-Stokes equations to predict the flow through a wind tunnel wall slot. The computations are in qualitative agreement at Mach number 0.9 with the experiments of Berndt and Sörensen, Fig. 1. The computational model is being extended to three dimensions (3-D) to calculate the slot flow in a two-dimensional (2-D) slotted test section using the time-averaged compressible Navier-Stokes equations. The extension is expected to take two years to complete. Laminar flow will be considered the first year; an algebraic turbulence model will be added the second year.

Ramaswamy and Cornette[2] have completed development of a computer code to predict the supersonic flow development in 2-D slotted-wall wind tunnels with arbitrary slot shapes. The formulation uses the method-of-characteristics equations and nonlinear wall boundary conditions. The calculations agree well with available experimental data. An extension of the method to axisymmetric configurations is planned.

Mercer et al.[3] have used the Jameson-Caughey finite-volume algorithm with the 3-D full-potential equations in conservative form to represent the flow about swept wing models in adaptive-wall wind tunnels. Either the velocity normal to the walls or the pressure distribution must be prescribed as a boundary condition. The program is being used at AEDC as a numerical simulation tool for adaptive-wall research.

X. Vaucheret, ONERA, has completed parametric studies on a computer[4] which suggest an optimization of the height-to-width ratio for a porous or slotted test section to reduce both the drag and angle-of-attack wall corrections[5] for typical models. A. L. Bleekrode and J. Smith,[6] NLR, have used the vortex lattice method to consider the proportions of the test section and the position of the model to reduce the lift interference with different ventilated walls. Karlsson and Sedin,[7] FFA, have analyzed the optimal slot configurations for axisymmetric flows. F. W. Steinle and E. R. Pejack,[8] NASA-Ames, have considered the effect of the number, the placement, and the size of slots as a function of the Mach number, the sweep angle, and lift distribution of the model. They found that the sidewalls should have eight times the effective porosity of the horizontal walls to minimize upwash and curvature effects.

Theoretical developments at AEDC pertaining to an adaptive-wall test section include an analytical proof of the convergence of the adaptive-wall iterative procedure to the interference-free condition;[9] development of two-[10] and three-dimensional[11] finite difference codes which solve the transonic small perturbation equations for the exterior flow region using flow angle and pressure as the control surface variables; development of a

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*Some of the research reported herein was performed by the Arnold Engineering Development Center (AEDC), Air Force Systems Command. Work and analysis for this AEDC research were done by personnel of Calspan Field Services, Inc., operating contractor of the fluid dynamics test facilities at AEDC. Further reproduction is authorized to satisfy needs of the U. S. Government.

"one-step" formula for transonic two-dimensional,[10] axisymmetric,[12] and two-dimensional supersonic flows which allow unconfined flow conditions at the control surface to be computed in one iteration for subcritical flows; and development of an accelerated convergence formula for three-dimensional subcritical flows to reduce the required number of adjustments for wall convergence. Work is continuing to develop methodology to use measurements on two control surfaces and investigate the use of several combinations of flow variables as the boundary criteria for the external calculations, to improve the speed of the external region codes, to investigate truncation effects resulting from a finite length test section, and to develop a three-dimensional closed-loop control algorithm.

The development of techniques for post-test interference assessments in conventional and adaptive-wall test sections using measured and inferred boundary conditions is continuing at NASA-Langley,[13] NAE,[14] ONERA,[15] NLR,[6] and RAE. All of the methods are presently for two-dimensional data. Although different algorithms are used, the calculated corrections are essentially the same: one of the test cases (the BGK 1 airfoil in the NAE 5 x 5 ft wind tunnel) is given (Fig. 2). Another comparison will be made in the near future using the CAST 7 airfoil being tested in several European wind tunnels. M. P. Carr, ARA, is developing a full-potential code using a method similar to the work of Murman[16] who uses the transonic small perturbation approximation.

Research is continuing to learn how best to use the measured boundary conditions and to assess the validity of the calculated corrections. It should be noted, however, that even if the interference perturbation field is well determined, wall-induced interference gradients or curvature of the flow may exist which do not correspond to any free-air condition, thereby making correction applications difficult,[16,17] especially for drag measurements.[18]

III. EXPERIMENTAL STUDIES

Flight tests of the AEDC 10-deg cone and correlation with wind tunnel data have been completed.[19] The results show that flight end-of-transition Reynolds number can be reproduced in the quietest solid- or slotted-wall wind tunnels up to Mach number 1.2. At higher Mach numbers there is substantial disagreement between flight and the wind tunnel data. An empirical correlation was developed, Fig. 3, which shows transition Reynolds number to be a power function of the noise environment and independent of Mach number and unit Reynolds number. Experiments with another 10-deg cone provided by NLR have been conducted at NAE, ONERA, FFA, and NLR. Additional experiments are planned.

The effect of the sidewall boundary layer on 2-D wind tunnel data continues to be of concern. Barnwell at NASA-Langley[20] has derived a modified Prandtl-Glauert rule which seems to provide a better data correlation at least at low speeds. An effective compressibility factor is defined as

$$\overline{\beta} = \left[1 - M^2 + (2 + H - M^2)\ \frac{2\delta^*}{b}\right]^{1/2} \tag{1}$$

where M is the free-stream Mach number, H the boundary-layer shape factor, δ^* the tunnel-empty boundary-layer displacement thickness at the position of the model, and b the tunnel width. The effect of using $\overline{\beta}$ is shown in Fig. 4. Research is continuing to assess the use of the $\overline{\beta}$ for transonic speeds.

Additional work with the sidewall boundary layer has been reported by Chan[21] who advocates that suction begin upstream of the airfoil and continue well downstream to achieve true two-dimensional flow over the airfoil. His data show that once suction is removed the boundary layer rapidly recovers to a growth typical of flow along a flat plate. However, with suction, properly applied, 2-D flow can be maintained with no adverse effect caused by some oversuction.

Jacocks[22] conducted an extensive experimental and theoretical investigation to define the crossflow characteristics of slotted and perforated wind tunnel walls. Five contoured wall configurations were used in a 2-D tunnel to generate pressure distribution along various ventilated configurations on the opposite wall. Typical results in Fig. 5 show that the wall crossflow characteristic, $dC_p/d\theta$, is very nonlinear and model dependent. The data in Fig. 6 indicate the Mach number dependence. The study also showed the wall cross-flow characteristic to be very dependent upon the local boundary-layer displacement thickness, which is modified considerably by the model-induced pressure gradient along the wall. Investigations in the NAE two-dimensional facility[23] also indicated that the boundary layer has a considerable influence on the wall crossflow. The task of formulating a theoretical representation of a ventilated-wall boundary condition seems very formidable. Nevertheless, experiments are being conducted by Everhart and Sewall at NASA-Langley with the goal of obtaining a general form of the slotted-wall boundary condition and at the City University, London[24] on perforated walls and at AMD.BA on porous materials.[25] Some means to measure accurately one or two components of the flow near the wall have been developed using rails[26] and lasers.[27]

Most of the effort concerned with transonic test section development is being devoted to adaptive-wall research. The research may be divided by configurations into three basic categories--compliant, slotted, and porous walls.

Compliant Walls. The first transonic tests with compliant walls were reported by ONERA (AGARD Meeting, June 23-24, 1976). The tests were conducted on a two-dimensional NACA 64A010 airfoil[28] using a linear or transonic small perturbation code for the exterior flow computation. Tests have also been completed with a NACA 012 airfoil for conditions at which the supersonic region reaches the wall.

A new test section (38 x 38 cm) with removable adaptive walls (Fig. 7) has been constructed at ONERA-CERT for the T2 induction-driven wind tunnel and validation tests reported.[29] A direct connection between the computer and the jacks controlling the wall shape is planned for a forthcoming CAST 7 airfoil test.

Goodyer and Wolf[30] have succeeded in obtaining essentially interference-free data on a two-dimensional NACA 0012-64 airfoil at Mach numbers up to 0.89 in a solid, compliant-wall wind tunnel. At the maximum condition, the supersonic region reached both the upper and lower walls. Reflection of the terminal shock system expected by most people did not occur. A comparison of the slope of the linear portion of the normal-force versus angle-of-attack curve, $dC_L/d\alpha$, obtained in the compliant-wall tunnel with similar reference data from the NASA-Langley 19 x 6 tunnel is presented in Fig. 8. The study is presently limited by the applicability of the linearized theory being used to perform the convergence calculations. Conversion to transonic small perturbation theory is planned. In addition, the use of the tunnel for three-dimensional adaptive-wall research is being explored.

A 9 x 9-in. three-dimensional tunnel has been constructed at AFFDL, which utilizes solid sidewalls and flexible-rod walls on the top and bottom, Fig. 9. The blowdown tunnel has a maximum capability of Mach number 1.25 at a total pressure of 4 bars. Preliminary shakedown has been completed, and tests are planned using a three-dimensional fighter configuration.

At Berlin Technical University the group of U. Ganzer operates a 2-D adaptive-wall test section in a fully automatic mode.[31] The adjustment of the flexible walls is controlled by a process computer. An average of three to four iterations is needed for the adaptation of the wall with the NACA 0012 airfoil at high angles of attack or at supercritical condition. Computer time for each iteration is eight seconds. A test section for 3-D model tests has been designed with eight walls adaptable in an identical way to the 2-D test section (Fig. 10). A particular problem in this design is the sealing of the eight corners. It has been demonstrated that spring steel laminations provide an adequate solution to the sealing problem.

In another 3-D concept being studied at DFVLR,[32] the test section is planned to be a 0.8-m-diameter deformable rubber tube used in conjunction with an existing blowdown wind tunnel (Fig. 11).

A very specialized application of the compliant-wall concept is being pursued at NASA-Langley in connection with research to develop a laminar-flow-control wing. By using existing two-dimensional inviscid and boundary-layer computational tools, a modification to the 8-ft pressure tunnel has been designed to contour the tunnel walls to conform to the streamlines around a swept supercritical wing spanning the tunnel. The tests are designed to be conducted at a supercritical lifting condition with a model which results in a tunnel height-to-chord ratio of less than unity. The design method has been checked using data from the NASA-Langley 6 x 19-in. wind tunnel operating with a solid compliant wall. A comparison of the measured and calculated wall shape to produce interference-free data on a two-dimensional NACA 0012 airfoil is shown in Fig. 12.

Slotted Walls. Research on the slotted adaptive-wall configuration is being conducted at NASA-Ames.[27] The non-return two-dimensional wind tunnel, Fig. 13, is equipped with slotted walls and 20 segmented plena. Velocities normal to the walls are measured along two lines with a one-component laser velocimeter. Tests are being conducted with a NACA 0012 airfoil, providing a tunnel height-to-chord ratio of 1.7. A computer is being used to control all aspects of the convergence process to eliminate wall interference, except actuation of the plena pressure control valves. Airfoil pressure distributions before and after convergence are shown in Fig. 14. Tests using a sidewall-mounted three-dimensional wing are planned in the future.

AFFDL has investigated the effect of solid sidewalls on three-dimensional force data.[33] Tests using a 0.92-percent blockage fighter configuration were conducted with solid and slotted sidewalls by adjusting the top and bottom walls so that the total porosity remained constant. Although the lift and pitching-moment data for the two configurations agreed well, drag data values obtained with solid sidewalls were lower than with slotted sidewalls at the higher subsonic Mach number (Fig. 15). Steinle and Pejack[8] and data obtained in the AEDC 4-ft Aerodynamic Wind Tunnel (4T) operating in semi-adaptive mode both indicate that sidewalls should have more open area than the horizontal walls. Therefore, the hope that solid sidewalls could be used for flow-visualization purposes in conjunction with the adaptive-wall concept in three-dimensional testing does not seem too bright for use during final performance testing. Of course, the use of solid sidewalls to obtain flow-visualization information during development testing can be a valuable test technique.

FFA has continued the research on axisymmetric test sections,[7] following the theoretical work of Berndt,[43] based on an improved inviscid slot crossflow model, an approximate perturbation velocity potential, and a pressure balance across each slot. Quadratic terms in the pressure equation are retained. The effective width of the slot is determined using experimental data. It is intended that eventually the slot width will be adjusted prior to a run to provide an interference-free transonic test section. In the low supersonic range the boundary condition to achieve interference-free data is being studied with a lifting wing-body model[35] and appears quite different from the criteria[36] developed with a cone-cylinder model at zero angle of attack. A test section with interchangeable variable slots and perforated plates is planned to obtain the conditions needed to perform tests at subsonic and supersonic conditions.

Porous Walls. AEDC has conducted experiments with both two- and three-dimensional porous walls. The two-dimensional experiments using a NACA 0012 airfoil[10] indicated that two important parameters--the upstream static pressure and the wall minimum pressure in the vicinity of the model--must be correct for unconfined flow to be achieved. Adjusting the upstream pressure to the unconfined flow conditions compensates for model blockage, whereas matching the required minimum pressure along the control boundary in the vicinity of the model significantly reduces the lift interference. Both parameters could be matched simultaneously with uniformly variable-porosity walls by adjusting plenum pressure, resulting in essentially interference-free model pressures. It is significant that the wall pressure distribution between the correct upstream value, the correct minimum pressure, and the correct downstream pressure was not critical to achieving unconfined flow.

AEDC three-dimensional experiments have been conducted with the model shown in Fig. 16. The lifting sections are NACA 0012 airfoils perpendicular to the leading edge. The model contains two 48-port Scanivalves® and a six-component balance. Data considered interference-free have been obtained in AEDC Propulsion Wind Tunnel (16T) from Mach numbers 0.5 to 1.05 and total pressures from 0.47 to 1.42 bars at an angle of attack of ±6 deg with boundary-layer transition both fixed and free. The experimental data[11] were obtained in AEDC Aerodynamic Wind Tunnel (4T) operating in a semi-adaptive mode by varying each wall porosity and plenum suction independently. Flow angle and static pressure in the vicinity of the walls were used as boundary conditions for the adaptive-wall calculations. The results showed that unconfined flow could be achieved for the wing at Mach numbers up to 0.90 with different uniform porosities on each wall, but not simultaneously with interference-free conditions at the tail. A typical example of the wing and tail pressure distribution is shown in Fig. 17.

IV. RECOMMENDATIONS

Although progress since Ref. 1 was written has not been as much as most people would like, a better understanding of interference phenomena related to the wind tunnel test section is emerging. However, much work remains. In an effort to guide the remaining work, the following recommendations are made:

1. The primary goal of present test section research should be to develop test section configurations that minimize the wall interference to the extent that the residual interference may be computed with confidence from the measured boundary conditions. Of course, the best post-test interference assessment techniques, based on the measurements of components of the perturbation field at a control surface (or two) and the means to achieve the required measurement accuracy at sufficiently numerous points, must also be perfected.

2. The combined use of experiment and computation should continue in order to enhance the understanding of aerodynamic phenomena and the limitations of both the experiment and computation.

3. The most successful results come from experiments, either numerical or physical, which are well designed to answer specific questions. Therefore, efforts to generalize experimental methodology do not appear too productive. However, statements about certain cautions are appropriate: (a) It is becoming evident that measurement of the upstream and downstream boundary conditions is difficult to define with certainty. One must understand how the measurement of free-stream conditions relate to the particular wall configuration under investigation or being used. (b) It is insufficient to correct Mach number without recomputing all data values affected by the Mach number, e.g., pressure coefficient. (c) One should thoroughly examine the applicability of reference data and assess the effects of Reynolds number, flow quality, manufacturing tolerances, sidewall boundary layer in two-dimensional tests, and support system interference in three-dimensional tests on the data comparisons.

4. There appears to be no better airfoil than the NACA 0012 for adaptive-wall research. However, the risk is finite that wall configurations will be developed which do a good job for the 0012 and not other classes of airfoil. Therefore, before any configuration is implemented it should be checked with several airfoil classes (perhaps the CAST-7 which has an ample existing data base is a good second candidate). It is felt that the supercritical airfoil will provide the most severe test of an adaptive-wall configuration. However, because of its sensitivity to flow quality, Reynolds number, and manufacturing tolerances, it will be very difficult to establish a good set of interference-free data for such an airfoil.

5. It was concluded that standardization of models, blockage ratios, and other parameters during the adaptive-wall development process would not be particularly fruitful. Nevertheless, each developing adaptive-wall concept should be pushed sufficiently far to determine its limits for producing correctable data.

6. A full-potential formulation of the exterior flow-field computation should be accomplished to determine if any limitations are caused by the small perturbation theory.

7. All of the post-test interference assessment techniques developed to date have been for two-dimensional tests. Similar techniques for three dimensions are urgently needed. The technique is applicable to present wind tunnels as an interference assessment tool.

8. There is also a need for fast approximate techniques for the exterior flow-field calculations so that small computers can be used for the adaptive-wall iteration process.

9. Research to understand better the crossflow characteristics of ventilated walls, particularly with shock-wave interactions, is needed to aid in the design of adaptive or passive wind tunnel walls.

10. Correlation studies, such as the ONERA calibration model studies and the AEDC 10-deg cone studies, are very useful in providing identification of, and insight into, existing problems. Therefore, such tests are encouraged.

11. Spatial and temporal (both low and high frequency) flow-field definitions of existing tunnels are needed to assess properly tunnel-to-tunnel differences and provide information on how uniform the tunnel flow fields should be. Quantities that should be measured include Mach number, flow angularity, temperature, total pressure, turbulence, and noise.

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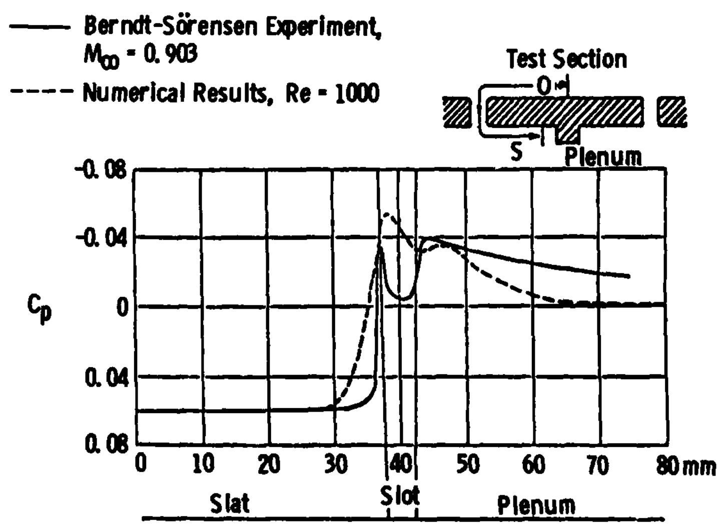
a. Inviscid Crossflow Streamlines

b. Viscous Crossflow Streamlines



c. Pressure Variation Around Slat

Figure 1. Flow Through a Wind Tunnel Wall Slot

Method	Mach Number Increment	Angle-of-Attack Increment, deg
NAE Canada (Mokry, Ohman)	-0.015	-0.67
ONERA France (Capelier, Chevallier, Bouniol)	-0.015	-0.67
NLR The Netherlands (Smith)	-0.015	-0.59
NAL Japan (Sawada)	Theory does not consider Mach number increments.	-0.58
NASA Langley (Kemp)	-0.014 -0.015	-0.68 -0.64

Figure 2. Post-Test Interference Calculations, 2-D BKG-1 Airfoil, NAE 5 x 5-ft Wind Tunnel, M = 0.784, α = 2.56 deg (Run 20914/4)

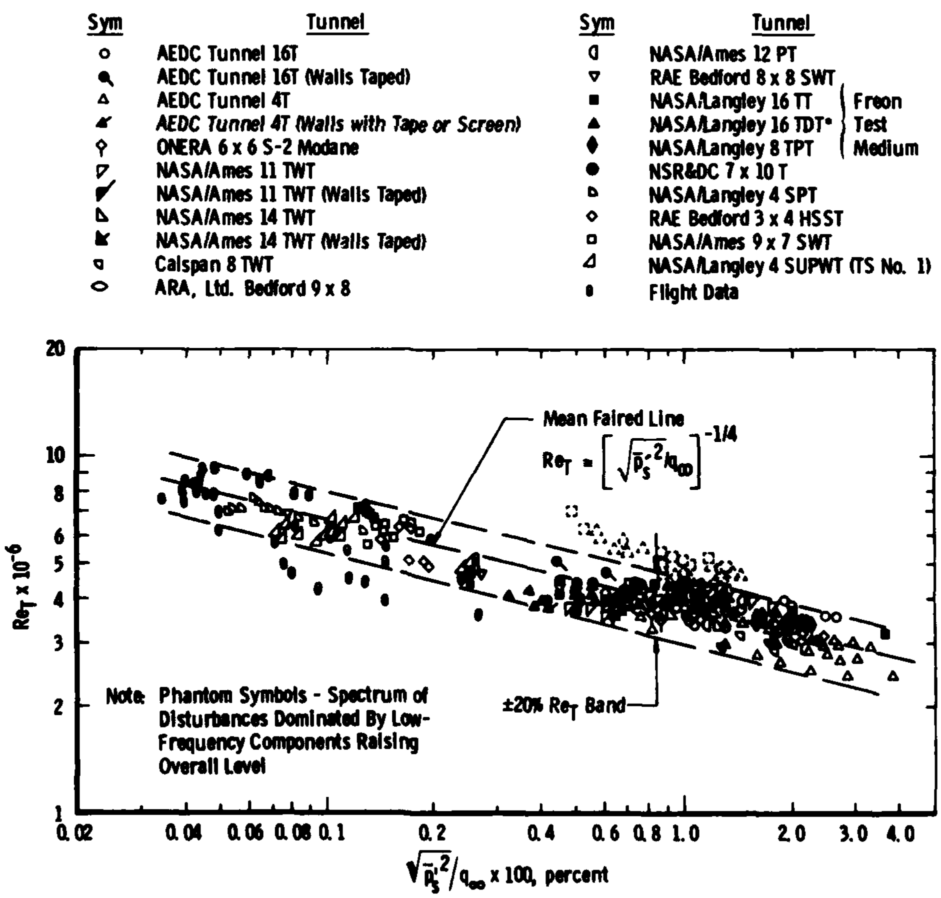


Figure 3. End of Transition Reynolds Number on the AEDC 10-deg Cone

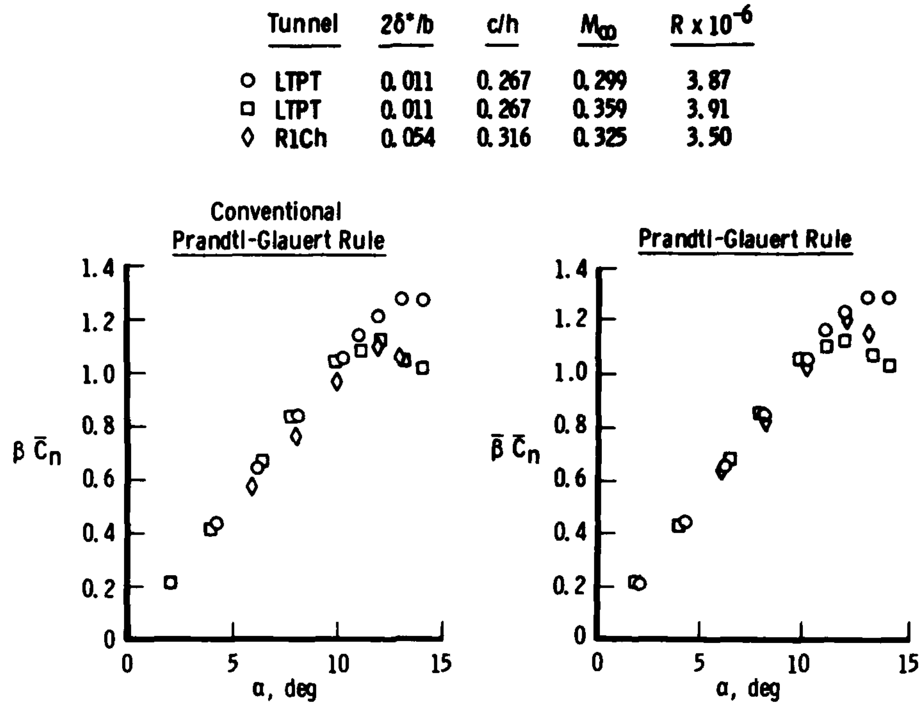


Figure 4. Correlation of Wind Tunnel Data with Modified Prandtl-Glauert Rule

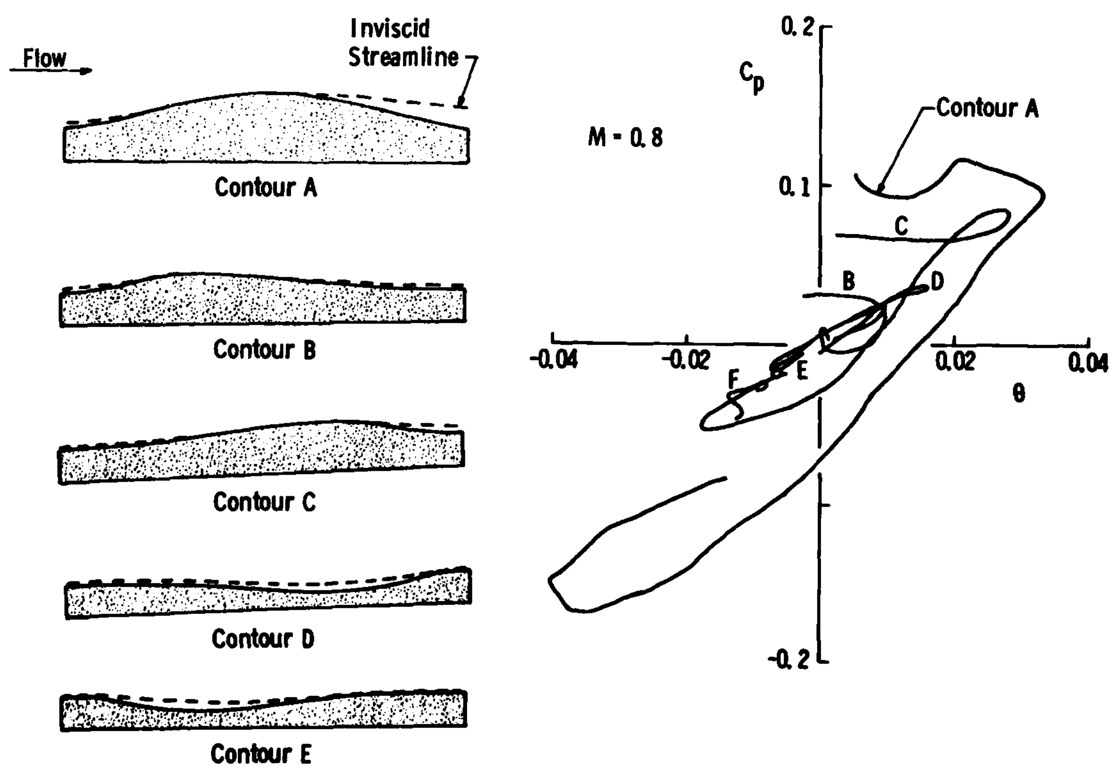


Figure 5. Crossflow Characteristics of 6-percent Inclined Hole Wall, M = 0.8

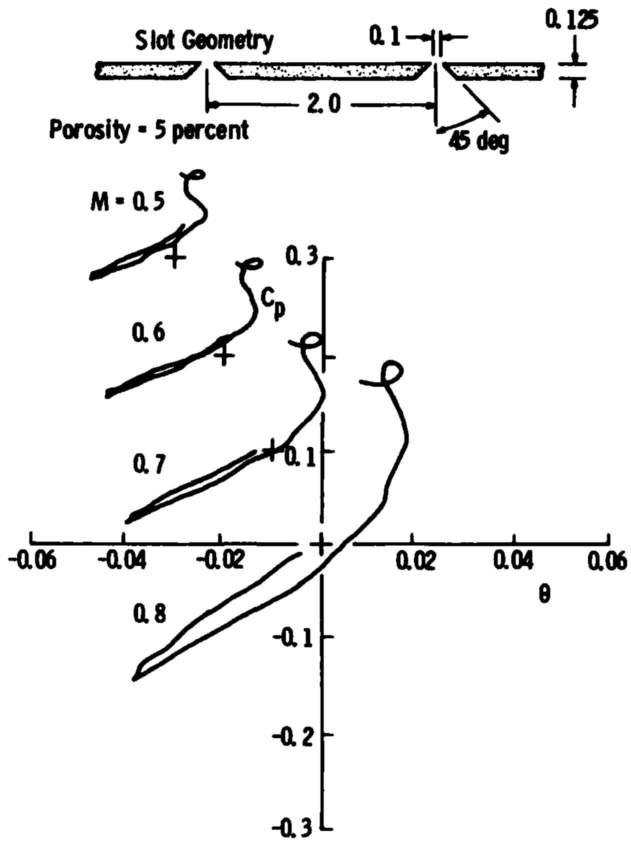


Figure 6. Slotted-Wall Crossflow Characteristics

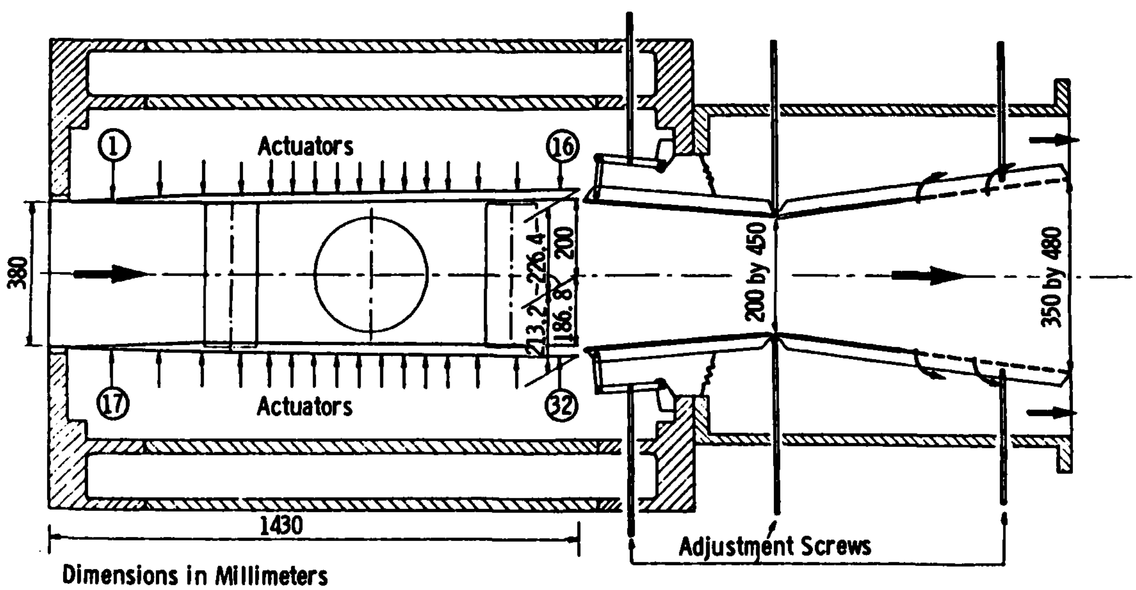


Figure 7. Tunnel T2 Equipped with Adaptable Walls

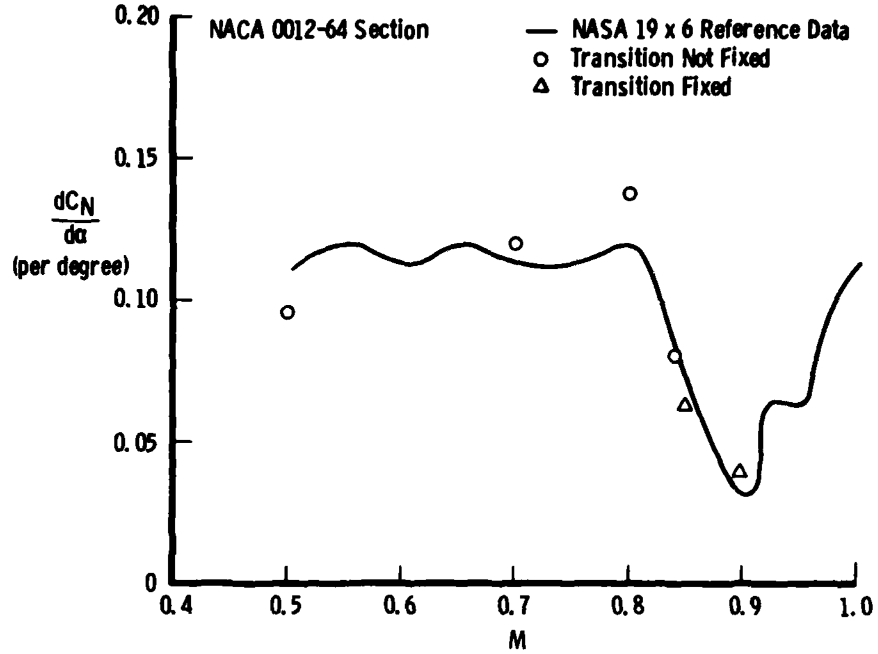


Figure 8. Comparison of Normal-Force Slope Obtained in the Self-Streamlining Wind Tunnel with Reference Data

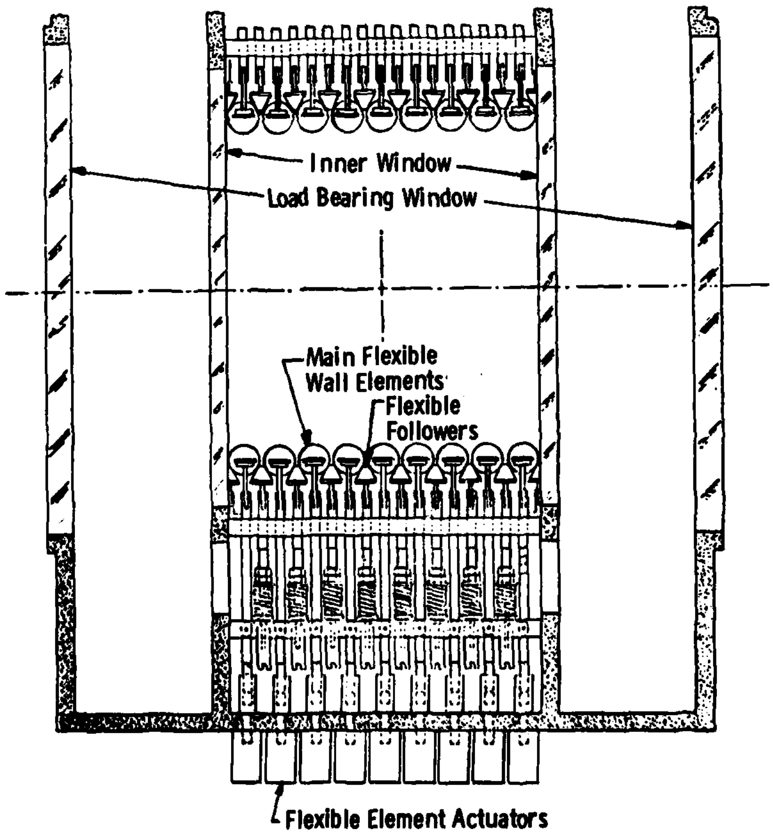


Figure 9. AFFDL 9 x 9-in. Pilot Tunnel with Solid Sidewalls and Adaptive Upper and Lower Walls

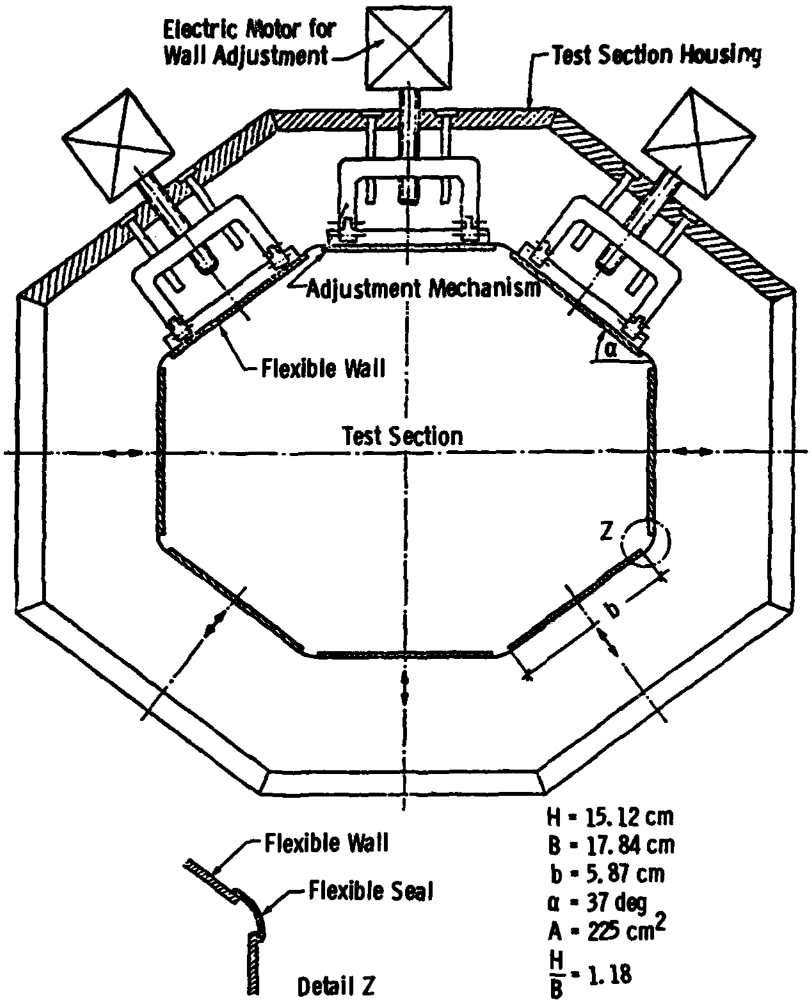


Figure 10. Technical University of Berlin 3-D Adaptive-Wall Wind Tunnel

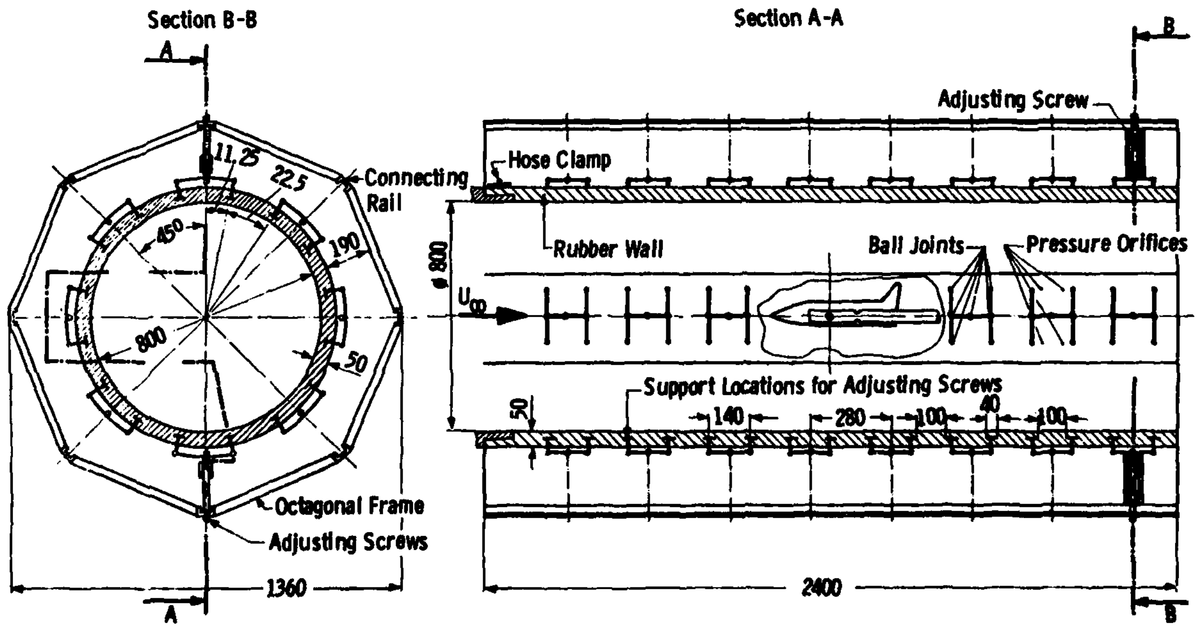


Figure 11. DFVLR Test Section with Expandable (Rubber) Walls

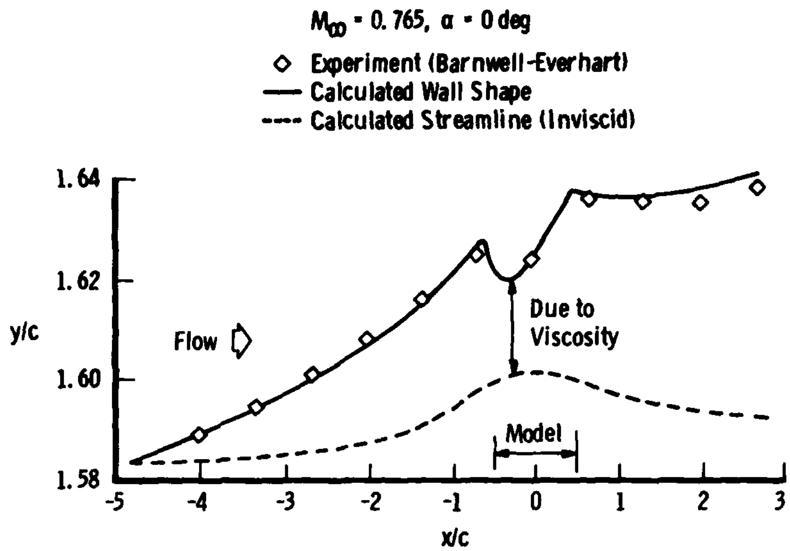


Figure 12. Comparison of Flexible Nonporous Wall Shapes for a NACA 0012 Airfoil Test

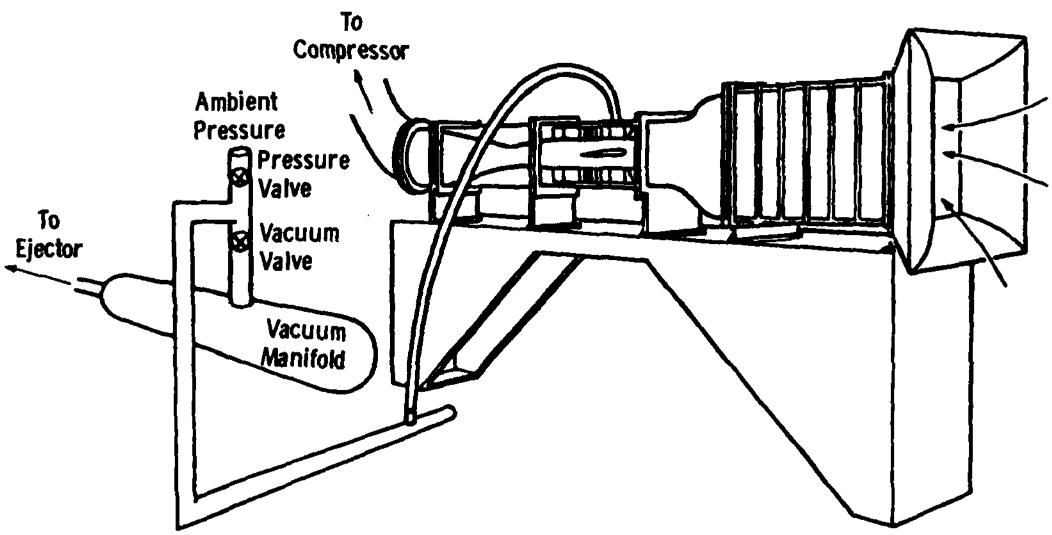


Figure 13. Ames 25 x 13-cm Adaptive-Wall Wind Tunnel

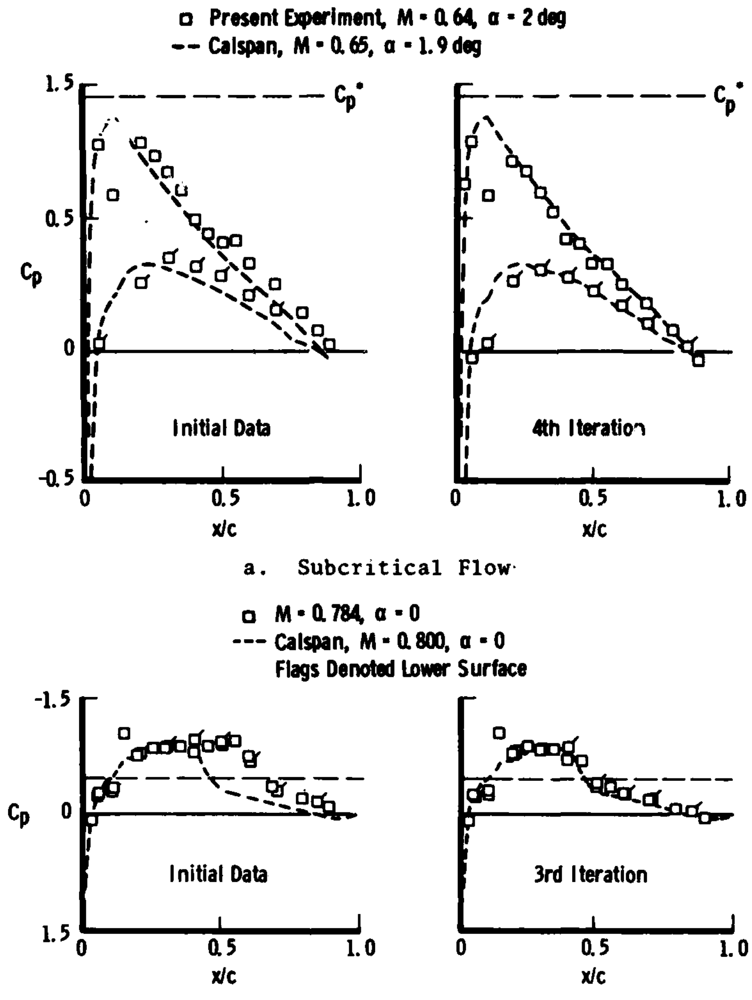


Figure 14. Converged Solution in the NASA-Ames 25 x 13-cm Adaptive-Wall Tunnel

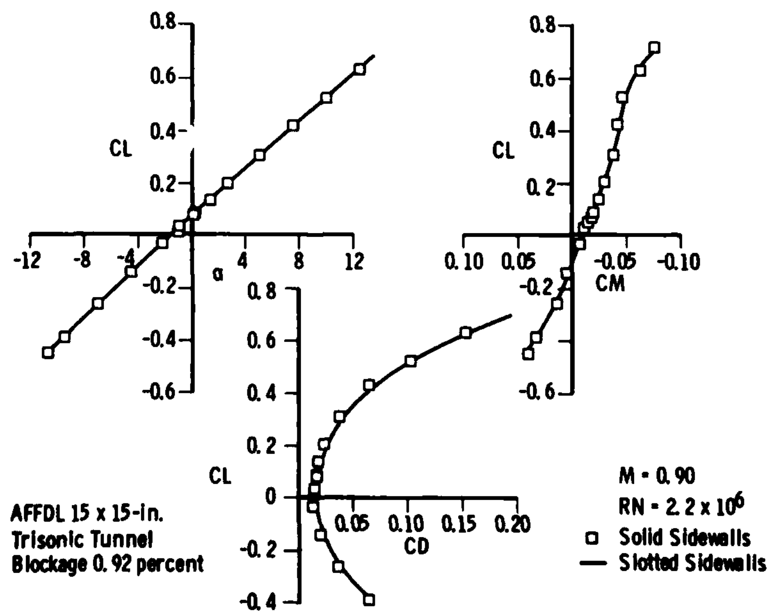


Figure 15. Comparison of Solid and Slotted Sidewalls at M = 0.90, Overall 6-percent Porosity in Each Case, AFFDL 15 x 15-in. Trisonic Tunnel

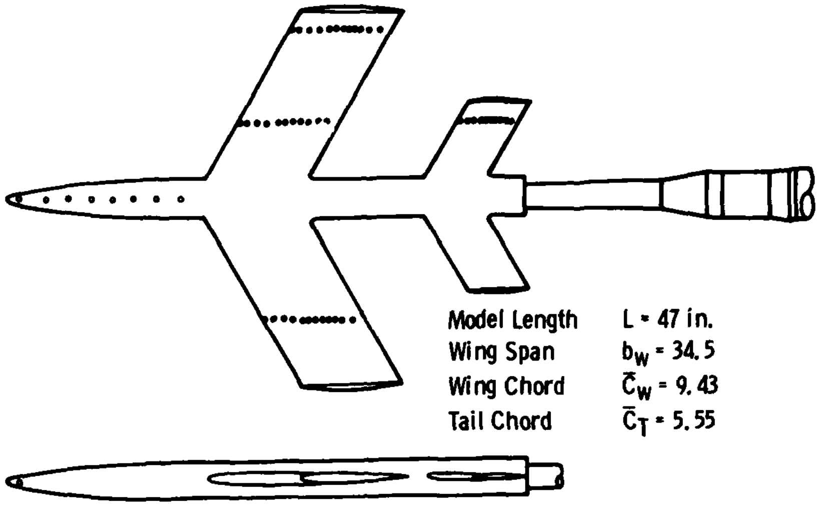


Figure 16. AEDC Three-Dimensional Wall Interference Model

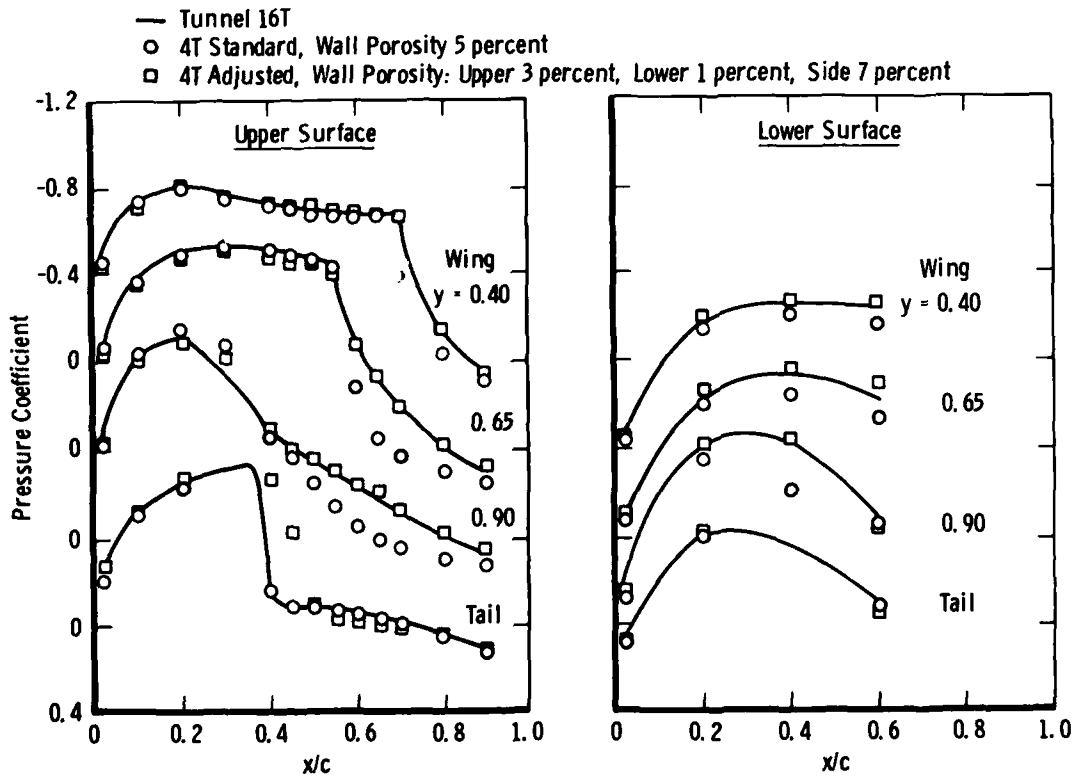


Figure 17. Model Pressure Distributions from Tunnel 4T Operating in Semi-Adaptive Mode, M = 0.9, α = 4 deg

APPENDIX 2

REPORT OF THE CONVENERS GROUP ON CRYOGENIC TEST TECHNOLOGY

by

L.Wayne McKinney
NASA-Langley Research Center
Hampton, Virginia 23665, USA

and

R.J.North
Technical Group ETU
c/o National Aerospace Laboratory NLR
1059 CM Amsterdam, The Netherlands

Edited by
E.C.Polhamus
307 Mistletoe Dr
Newport News, Virginia 23606, USA

SUMMARY

This report summarizes Convener Meetings on Cryogenic Test Technology held in the United States and Europe. It includes a brief summary of the material presented and possible areas of cooperation discussed at the two meetings. Priorities are suggested and recommendations regarding future meetings are included.

LIST OF SYMBOLS

A/C	Aircraft
$\bar{c}$	Mean aerodynamic chord
C_f	Skin friction coefficient
C_L	Lift coefficient
c_p	Specific heat at constant pressure
C_{VN}	Charpy impact energy for Vee-Notched specimen
ΔC_p	Incremental pressure coefficient
d	Orifice diameter
K	Kelvin
K_{IC}	Plain strain fracture toughness
k_a	Surface roughness height
M	Mach number
M_L	Local Mach number
m	Meters
N	Newtons
P	Pressure
q	Dynamic pressure
R	Rankine
$R_{\bar{c}}$	Reynolds number based on $\bar{c}$
RT	Room temperature
T	Temperature
σ_u	Ultimate tensile strength
σ_{yp}	Yield strength
α	Angle of attack, degrees
δ^*	Boundary layer sublayer thickness

Subscripts

t	Stagnation conditions
∞	Free stream conditions

1. INTRODUCTION

This report is based on meetings on Cryogenic Windtunnel Testing Technology held at NASA Langley Research Center, USA, September 23 to 25, 1980, and at ONERA/CERT, Toulouse, France, October 28 to 31, 1980. The meeting at Langley was attended by 25 specialists from NASA and aerospace companies and other government agencies in the USA, interested in using the National Transonic Facility (NTF). The European meeting was attended by 12 specialists from the various national research establishments and from industry interested in the development and eventual use of the European Transonic Windtunnel (ETW). The two meetings differed somewhat in character due largely to the different status of the NTF and ETW Projects.

The NTF was conceived and designed to satisfy the national high Reynolds number testing needs of the U.S. Department of Defense, aerospace industry, university community and NASA. It is being constructed by NASA at the Langley Research Center and is scheduled to be ready for calibrating by mid-1982. Along with the construction of the NTF Langley has had for several years an in-house research and development program on cryogenic testing technology to support the operation of the facility. This program, which includes both theoretical and experimental studies using the 0.3 meter Transonic

Cryogenic Tunnel as a testing facility, represents most of the active effort in cryogenic testing technology in the U.S. Therefore, the meeting focused on a review and discussion of the status and goals of this program.

The European Transonic Windtunnel (ETW) Project is a cooperative effort between France, Germany, The Netherlands and the United Kingdom. The project is in the preliminary design stage with proposals and cost data being reviewed by the participating countries. Along with the design studies for the ETW, there is an ETW Cryogenic Technology Program which is composed of activities in the four participating countries. Only a minor part of the work is funded by the project itself with the major part being funded by national agencies or aircraft firms in the countries concerned. This activity is promoted by a working party of the ETW Project composed of persons of such status in their own countries as to be able to influence their national programs. The overall program has been briefly summarized previously [1-2] and it includes work on selected topics such as model design and construction, material selection, force balances, instrumentation, and condensation and real-gas effects. Attendance at the Toulouse meeting was limited mainly to those concerned with managing the various aspects of the ETW Cryogenic Technology Program.

The meetings on each side of the Atlantic were not expected to be analogous because of the different states of development of the cryogenic tunnel projects in the USA and Europe. Although they differed in character and content they shared common goals: (1) to give the attendees up-to-date status reports on the windtunnel projects and cryogenic technology programs; (2) to provide the convener from each side of the Atlantic an overview of the situation on the other side; (3) to give the attendees not directly involved with the NTF and ETW projects opportunities to offer advice and comment; (4) to provide a forum for discussion of goals and priorities, and (5) to consider areas of possible consideration.

This report provides a brief summary of the material presented and areas of cooperation discussed. It suggests priorities and concludes with recommendations regarding future meetings.

2. DISCUSSION

In presenting and discussing the material from the two meetings, the following outline is used:

CRYOGENIC WINDTUNNEL PROJECTS

MODEL DESIGN AND CONSTRUCTION

- Design Considerations
- Tolerances
- Model Surface Finish
- Orifice Induced Pressure Errors
- Design Analysis
- Selection of Materials
- Model Design and Fabrication Projects

INSTRUMENTATION

- Force Balances
- Pressure Measurements
- Temperature Measurements
- Model Attitude
- Dynamic Instrumentation

TEST TECHNIQUES

- Model Deformation
- Flow Diagnostics
- Remote Control Manipulators

FLOW PHENOMENA

- Minimum Operating Temperature
- Real Gas Effects
- Effect of Wall Temperature Ratio
- Liquid Nitrogen Injection

SUMMARY

RECOMMENDATIONS

3. CRYOGENIC WINDTUNNEL PROJECTS

There are three (3) major cryogenic windtunnel facilities in the United States: The 0.3 Meter Transonic Cryogenic Tunnel and the National Transonic Facility at the Langley Research Center, and the McDonnell Douglas Transonic Blowdown Tunnel at El Segundo, California. Description of these facilities have appeared periodically in the literature [3-13] with the latest and most up-to-date being those published in the AGARD Lecture Series 111, May 1980. The 0.3 meter TCT first became operational in 1973. The Douglas Blowdown Tunnel first operated in 1980, and the NTF will be operational in late 1982. Descriptive characteristics are listed in Table 1.

The European Transonic Windtunnel (ETW Project [14]) has been underway for about three years. A preliminary design study has been completed and cost estimates made. The preliminary design proposals are being reviewed in the light of comments from the aeronautical industry and research establishments. The general characteristics of the proposed tunnel are described in reference 14. However, the Steering Committee of the project has recently agreed with the European industry, as represented by AECMA, that tunnel specifications should be revised as follows:

- test section dimensions 2.40 m x 2.0 m
- maximum total pressure 4.5 bar

In addition, the pressurized model access lock previously proposed will be replaced by a simpler unpressurized design. Preparations are in hand for the next phase including selection of the site; the four possibilities being Köln, Le Fauga, Noordoostpolder and Farnborough.

A pilot tunnel [14] (PETW) about 1/8th scale is being constructed by the ETW Project and will be installed at NLR Amsterdam: it is expected to be ready for operation in mid-1982. An ambient-temperature aerodynamic test-rig of the same size, to check aspects of circuit design, has been constructed and tested at DFVLR, Köln under contract with the ETW Project. At DFVLR Köln, it is planned to modify an existing concrete unpressurized low speed windtunnel for cryogenic operation (stagnation temperature = 100 to 300 Kelvin, velocity = 5 to 100 meters/sec.). The test section dimensions will be 2.4 m x 2.4 m and the insulation will be internal. It is expected that it will run once a day with a measuring period of 5 minutes during a run taking 12 minutes overall. Further, a blowdown open-jet (100 mm diameter) facility has been constructed to give Mach numbers between 0.4 and 0.9. It exhausts into open air or into a test chamber at about 0.3 bar; run times are about 10 - 20 minutes. It will be used for studies of mixing, measurement techniques, simple flow fields and plumes.

Two small cryogenic tunnels [15-16] are in operation at ONERA/CERT and a third is being converted to cryogenic operation. Their characteristics are included in Table 1. At ENSAE, nearby, an existing fan-driven, two-dimensional tunnel will be adapted to cryogenic operation with external insulation.

At the University of Southampton, Goodyer [17] has built a small (test section 0.1 m x 0.1 m) subsonic cryogenic tunnel with atmospheric total pressure and is developing a small pressurized cryogenic tunnel for educational purposes.

4. MODEL DESIGN AND CONSTRUCTION

The design of models for the various planned cryogenic high Reynolds number tunnels around the world will require the model designer, on a routine basis, to account for both the cryogenic and the high dynamic pressure environment at the same time, and some of the problems are discussed in the literature [18-20]. A considerable amount of experience with designing and testing simple models at cryogenic temperatures and elevated pressures has been obtained at the NASA Langley Research Center over the past eight years. This experience will be discussed in a subsequent part of this section; but generally it has indicated that thermal considerations on stresses and material characteristics can be accounted for in a relatively straightforward manner by applying good engineering design practices. However, even for simple models, difficulties in fabrication processes have been encountered with some stainless steel alloys with which machining experience and a knowledge of material changes at cryogenic temperatures is very limited. Windtunnels operating at relatively high stagnation pressures have, of course, been in operation throughout the world for many years and have continually provided a challenge to the model designer. In the case of the NTF and ETW, it is believed that overcoming the model problems associated with high loads will, in many cases be as difficult as those associated with the cryogenic environment. The basis for this statement and the various areas of concern to model designers and fabricators will be discussed in this section.

4.1 Design considerations

There are three basic considerations in designing models for the new high Reynolds number tunnels that will make the task of model design and fabrication more challenging than in the past. First are the thermal considerations associated with the cryogenic environment. These will require attention to such items as thermal stresses, fasteners, use of materials with dissimilar thermal characteristics, and material selection from the standpoint of strength properties and fracture toughness as a function of temperature. Second is the high stagnation pressure and associated high model loads and dynamics. In the case of all of the new transonic windtunnels in various stages of development in the United States and Europe, practical considerations of cost dictated test section sizes (2.5 meters maximum) such that cryogenic operation alone will not achieve the desired Reynolds number capability, therefore, they are designed for combined cryogenic and high pressure operation. To utilize these higher stagnation pressures will require a more detailed approach to model design such that the model and model components can be designed to lower margins of safety. This will involve more detailed analysis from both static and dynamic load considerations, better quality control during fabrication, and in some cases may involve extensive static proof loading and on-line monitoring of loads and dynamic response. While it is generally believed that the high dynamic pressures will often produce as great a challenge to the model designer as the cryogenic temperatures due to material stress limits, the more subtle effects of cryogenic temperatures and the new problems that will undoubtedly be encountered with increased experience cannot be overemphasized. The third area of consideration associated with the new windtunnels is model requirements due to the thin boundary layers encountered during high Reynolds number testing such as, tolerances, surface finish and orifice size and installation. Since the basic purpose of the new high Reynolds number tunnels is to achieve improved simulation of aerodynamic flow fields over the models, special attention must be paid to these areas.

The design of support stings for the high dynamic pressure conditions is also a concern due to both intereference and sting divergence considerations. A parametric study [26] has recently been completed at ONERA considering stresses in the sting, balance limitations (Task balance), divergence, and clearance at model base for both transport and combat aircraft. A number of examples of different models and sting lines were examined. At IMFL the feasibility of a composite sting is being examined [24].

The subsequent parts of this section will discuss in some detail the implications of all of the above mentioned considerations on model design and fabrication including past experience, ongoing activities and needed research and development. However, since dynamic pressure and associated model loads and dynamics is a fundamental consideration in most all aspects of the design problem, it is appropriate to look at what level of design dynamic pressure will be required for transport and fighter aircraft models. The most stringent of these requirements is for the very high Reynolds numbers available in the National Transonic Facility. The operating envelope for a Mach number of 0.8, shown in Figure 1, illustrates the dynamic pressure requirements for typical transport configurations. The range of Reynolds number with dynamic pressure for existing 2.0 to 2.5 meter ambient temperature tunnels is also shown for reference. For the A-300 Airbus size airplanes, full scale Reynolds number can be obtained in the cryogenic case at a dynamic pressure of approximately 1.0×10^5 newtons/square meter. This is roughly comparable to the maximum dynamic pressure capability in the Calspan tunnel with the injectors operating and illustrates the large increase in Reynolds number due to reduced temperature with model stresses no larger than obtained in current tunnels. To match full scale Reynolds number for transports the size of the Boeing 747, an additional 50 percent increase in dynamic pressure is required. The achievement of this test condition will dictate relaxation of the model design safety factors currently used, compensated by a more detailed design analysis.

The Reynolds number-dynamic pressure envelope for the NTF at a Mach number of 0.9 is shown in Figure 2 along with the Reynolds number requirements for a typical maneuvering fighter at altitudes from 3000 to 12000 meters. Although the required dynamic pressure varries greatly over this range, the model lift force (and model stresses) for simulation of a constant airplane load factor are nearly constant. This results from the fact that the temperature variation as a function of pressure (corresponding to condensation at a local Mach number of 1.4) results in a variation of Reynolds number with dynamic pressure between 3 and 12 thousand meters, that is essentially proportional to that of the airplane in the atmosphere. Therefore the simulation of a constant load factor over this altitude range results in a constant model lift force just as it will on the airplane. This is illustrated in Figure 3. As Reynolds number is increased at the minimum NTF temperature, the tunnel q is required to increase. If a constant airplane "q" or load factor condition is simulated, however, the model angle of attack and thus lift coefficient will be reduced and the resulting $C_L q$, or lift, will be constant with changing Reynolds number. If, for model design considerations, changes in wing span load distribution with changes in angle of attack are ignored, this constant lift load will result in the wing stress being approximately constant. Therefore, the stress limit will correspond to the maximum $C_L q$ which will impose a limit on maximum airplane g's or load factor that can be simulated at full scale Reynolds number. This limit is independent of the magnitude of Reynolds number. Therefore, the dynamics of the model/sting/balance configuration, which is a function of dynamic pressure, or q, will govern the maximum Reynolds number at which full scale conditions can be simulated. The effect of the $C_L q$ limit is summarized on Figure 4 which is basically an overlay to Figure 2 with some of the legend omitted for clarity. The open symbols represent flight conditions where, for a constant simulated load factor condition, the model load is constant. It is interesting to note that the strength requirements for a model tested in an existing tunnel (solid symbol) at a q of approximately 72,000 newtons per square meter and a lift coefficient corresponding to a given load factor at 12,000 meters are identical to what they will be in the NTF at any of the full scale conditions indicated by the open symbols for the same simulated load factor. This results from the fact that the increase in Reynolds number between the solid symbol and open circle corresponding to 12,000 meters altitude is due entirely to the benefit of cryogenic temperature operation. The point of this discussion is that both model strength and model/balance/sting system dynamics will play an important role in determining maximum usable NTF test capability for a given configuration.

4.2 Tolerances

Model fabrication tolerance requirements are difficult to determine because of the accuracies needed in experimental and analytical studies for defining these tolerances at transonic speeds; some work is being done at Dornier on this topic. Currently, transonic model tolerances are determined by past experience and the accuracy of the machines used to fabricate the model. Since the model tolerances do affect data accuracy and model costs, it is desirable to develop improved techniques for tolerance definition.

4.3 Model surface roughness

To obtain the data accuracy desired for most high Reynolds number transonic tests, it is desirable to provide a model surface roughness that will not produce a measurable aerodynamic effect. Some of the potential areas of surface roughness influence are skin friction, transition, shock wave location and boundary layer separation. More information exists on the effects of roughness on skin friction than the other two areas [21]. The current criteria for admissible roughness height is the maximum surface roughness height that will not affect skin friction. The data in Figure 5 show the variation of admissible roughness height, k_a, in a zero pressure gradient turbulent boundary layer, with Reynolds number $R_{\bar{c}}$, where mean chord $\bar{c}$, is taken as 0.20 m (0.65 ft). This mean chord is representative of a transport model sized for the NTF. Shown on Figure 5, for reference, are the maximum NTF Reynolds number, the Boeing 747 cruise

Reynolds number and the maximum Reynolds number for current tunnels. At a given Reynolds number, any roughness height falling below the admissible roughness curve in Figure 5 will produce no skin friction penalty. The shaded band on Figure 5 is the range of typically specified and achievable surface finishes for current transonic models. The current specified model surface finishes appear to be compatible with a significant part of the NTF Reynolds number range. However, as is noted on Figure 5, the admissible roughness curve is for a surface with uniformly distributed three-dimensional particles and as the photographs in Figure 6 show, the surface of a typical model does not resemble a uniform distributed particle roughness. Thus, an experimental program is planned at the NASA Langley Research Center to determine the equivalent distributed particle roughness for typical NTF model surfaces.

In order to carry out the above experimental program, a good definition of the topography of a typical model surface is needed. The instrumentation which is almost universally used to measure model surface roughness in model shops is the stylus profilometer type equipment. There are at least two potential problems associated with the stylus profilometer. These two potential problem areas are, roughness slope too steep and roughness frequency too high; it should be noted that the stylus radius is typically 2.5 microns (100 μ in.). Since there are no published data which verifies that the stylus profilometer accurately determines surface topography data on surfaces typical of high Reynolds number models, it is planned that the National Bureau of Standards (NBS) will compare the topography of a surface typical of NTF models as measured by a stylus profilometer and stereo scanning electron microscope. In addition, the stylus profilometer has great difficulty measuring surface finishes on curved surfaces similar to the leading edge region of wings. The leading edge region of the wing is the region, of course, where the boundary layer is thinnest and thus, is the region where the local skin friction is most sensitive to surface roughness. Thus, it is highly desirable to have the capability of measuring surface finish over the leading edge. Towards this end the NBS is developing a light scattering system to measure the surface finish accurately on surfaces with high curvature.

4.4 Orifice induced pressure error

As the Reynolds number increases and the boundary layer becomes thinner, its thickness can become small compared to the orifice diameter. Under these conditions, the orifice induced pressure error may not be negligible [21]. An additional orifice error, that may be significant in magnitude, can result from orifice imperfections. Although there are several types of orifice imperfections, experimental data exists only for a burr around the orifice. A burr can produce flow separation in the orifice causing additional streamline deflection. Some other types of hole imperfection which can produce pressure error are out-of-round orifices, particles in the orifice and the longitudinal axis of the orifice not normal to the model surface, to mention the most common.

Figure 7, reproduced from reference 21, illustrates the effect of Reynolds number on orifice induced pressure error. For reference, the maximum NTF Reynolds number, Boeing 747 cruise Reynolds number and the maximum Reynolds number available in current tunnels are shown. From these data, it may appear that a 0.13 mm (0.005 in.) diameter orifice is satisfactory for the complete range of NTF Reynolds numbers since the maximum error is only 0.008. However, all the data in Figure 7 are for $d/\delta^* < 4.0$, and since d/δ^* for the high Reynolds number conditions can be of the order of 100, erroneous conclusions may be drawn regarding the level of the orifice induced pressure error if only this data is applied. Further, just extrapolating the curves for the 0.51 mm and 0.25 mm diameter orifices to the high Reynolds number region can lead to erroneous conclusions. Therefore, a test program is underway at Langley to extend the data shown in Figure 7 to higher d/δ^* values and higher Reynolds numbers.

4.5 Design analysis

In view of material strength limitations, large aerodynamic loads will necessitate that many models for the NTF be designed to small safety factors. To insure that such a design is adequate, various detailed analyses and bench tests must be performed as the design progresses and the designer and the analyst must work closely in developing a suitable design.

The importance of the thermal analysis for cryogenic models should not be underestimated. Because of the tunnel transients, there will be thermal gradients in the various system components and temperature differences between mating parts. These effects must be evaluated since they can lead to high stresses or loose structural joints.

The cryogenic models will be subjected to various thermal transients. First, there is the initial cooldown period. Also, there will be changes in the tunnel test conditions. In order to make alterations to the models, the model must be heated. After model changes are made, the model may be subjected almost instantaneously to the cryogenic environment. This thermal shock will probably be the most severe transient for the model. The effects of these transient conditions on the entire model, balance and sting system should be examined. This means that several thermal math models may need to be developed in order to determine the time-dependent temperature distributions in the various parts. An evaluation of resulting gradients may show the existence of large thermal stresses. For example, the thermal shock that can occur after a model change will certainly cause a high surface stress on the model. The effects of thermal gradients and temperature changes on the numerous structural joints in the system must be investigated. Since a loss of joint stiffness could lead to divergence or flutter problems, special attention should be given to the model-to-balance joint and to the balance-to-sting joint. For these and other joints, appreciable preloads may be needed in order to avoid joint looseness. When preloading, consideration should be given to both the positive and negative temperature swings so as to avoid overstressing the joint. For models having a tongue and groove wing design, such as one of the NTF models, there is concern that slight temperature differences may develop between the leading and trailing edge portions of the wing. Any tendency for the two parts to contract differently spanwise could cause large shear stresses in the dowels which pass through the tongue and groove joint. In many cases, it is likely that instrumentation packages inside cryogenic models will be heated. Care must be taken to insure that these packages are properly insulated such that the gradient does not create a thermal stress problem.

In view of the potentially high aerodynamic loadings and large thermal gradients, a very thorough stress analysis will be required for the model and sting systems. The stresses in the various components of the system will probably need to be evaluated using both finite element and strength of material approaches. The thermal stresses will need to be studied using finite element models except in instances where the geometry and temperature distribution can be represented by a classical "theory of elasticity" problem whose solution is known. Since many models will be designed with small safety factors, much emphasis must be given to stress concentrations. There are numerous reports and handbooks available for determining stress concentration factors. Also, if necessary, stress concentrations can be evaluated by making detailed finite element models of the highly stressed regions. Generally, the highest stress will be due to the stress concentration around the orifices in the wings. The orifices are normally circular and this causes a stress concentration factor of three. Other sources of stress concentrations are dowels or shear pins. Whenever possible, care should be taken to avoid placement of pins in highly stressed regions. Also, consideration should be given to designing pins to have slight interference fits since this can increase the fatigue life. After determining the stress levels, the model design should be examined from fatigue and fracture mechanics viewpoints to insure adequate life.

A deformation analysis is essential to the design of highly loaded models. Because of the large deformations, many models will be built with a shape such that the model lifting surfaces will have the proper shape when loaded. Thus, it is necessary to be able to predict accurately the deflections of wings under aerodynamic loads. The aeroelastic and deformation analyses are dependent upon the development of accurate elastic mathematical models of the model and sing system. NASA has used two different types of mathematical models in the analysis; one, a beam representation of the wing and the other a finite element approach. It is important that the elastic mathematical models used in the analyses be verified by testing of the actual hardware. This is especially true if the design is marginal. The mathematical models can be confirmed by performing load/displacement tests, measuring natural frequencies, and by strain gage data. Also, joint effects, which are often unpredictable, can be evaluated by testing.

The aeroelastic analyses require the development of a mathematical model of the entire model, balance, and sting system. The aeroelastic analyses should consist of determining the natural vibration modes, using these modes as displacement functions in flutter and divergence studies, and performing any needed dynamic response analyses. It is thought that the flutter analysis, as well as the divergence analysis, must treat the entire system. As might be expected, recent vibration tests at Langley Research Center have shown appreciable differences in the modes and frequencies of modles mounted on and off of the system dynamic characteristics. Also, since aeroelastic divergence and flutter are of great concern for models that may be tested at high dynamic pressures, the analyses must give particular attention to the stiffness of structural joints. There are various computer codes available for performing flutter analyses. A system of programs at Langley called FAST for Flutter Analysis System is being used in the initial studies of the NTF models. The unsteady aerodynamics programs in FAST are based on the subsonic kernel function lifting-surface theory.

4.6 Selection of materials

Cryogenic temperatures can significantly reduce the fracture toughness of many materials which might be used in constructing windtunnel models. Conversely, high fracture toughness is considered essential for the highly loaded models because stresses in the vicinity of structural discontinuities will be quite high. These high stresses, if applied to relatively low toughness materials, may result in unacceptable critical flaw sizes. To preclude the possibility of developing such small critical flaws (which could be difficult to detect), a material survey was conducted by NASA Langley Research Center to determine which materials possessed adequate strength and toughness at cryogenic temperatures to be considered for model construction. The criteria selected by NASA was a Charpy V-Notch impact strength of 33.7 Meter-Newtrons (25 foot-pounds) at test temperature. The Fracture and Deformation Division of the U. S. National Bureau of Standards has developed a preliminary list of candidate materials [22]. NASA Langley has expanded this list to include several additional materials. A list of the materials considered by NASA Langley and their structural properties is presented in Figure 8. In addition to the structural characteristics, consideration must be given to such qualities as corrosion resistance, machinability, cost and availability. NASA has selected Nitronic 40 stainless steel as the material for the first model being fabricated for the NTF. Douglas Aircraft Company has been considering stainless steels (ARMCO PH 13-8), beryllium copper and composites to fabricate models for use in the DAC 4-CWT.

In Europe, a study ahs been completed at IMFL on materials and assembly methods for cryogenic windtunnel models. THe reports on this work consist of an extensive bibliography [23] and a report [24] on metals and assembly methods. The work on metals consisted of measurement of selected characteristics of two maraging steels (Marval 18 and 18H), a stainless steel(X17U PH), a carbon steel V300 (45SCD6), and a beryllium copper (STM25) over a range of temperatures from about 90K to room temperature. In addition, fracture toughness (K_{Ic}) was measured for Marval 18H and V300. Some tests were made showing the large effect of welding on the tensile strength of notched Marval 18H specimens. Experimental and theoretical investigations have been made on bolted and screwed assemblies using various combinations of metals of interest.

4.7 Model design and fabrication projects

NASA Langley is currently fabricating a transport model configuration with wing pressure orifices for the NTF. It is a clean wing model without nacelles or controls. It was designed for full scale Reynolds numbers assuming a L-1011 size airplane. Geometric characteristics are presented in Figure 9. The material being used is Nitronic 40 stainless steel which has bery good strength and fracture properties at cryogenic temperatures. NASA also has in design, a general research fighter configuration

shown in Figure 10. This model will have a four percent thick wing with pressure orifices. As will be noted from Figure 10, it does not include flow-through inlet simulation. The purpose of this model is to provide a general research model for early NTF research programs and address design and fabrication problems associated with highly loaded thin wings. Additionally, NASA is negotiating a contract study with the U. S. industry for model design studies of an actual single and twin engine fighter configuration to address the problems associated with flow-through nacelle configurations including sting mounting techniques.

Additional experience in the U. S. is being generated by industry. Douglas Aircraft Company is fabricating a model of the DC-10 for testing in their 4-Foot Cryogenic Blowdown Tunnel. The model has wing pressures, temperature sensors and flow-through wing mounted pylon nacelles. Lockheed Georgia Company, as aprt of a joint contract effort with Air Force Wright Aeronautical Laboratory, NASA Langley, and NLR Amsterdam, has fabricated a half model with a 1 meter span and pressure orifices for testing in the transonic tunnel at NLR. This model was designed for measurements of unsteady surface pressures and was designed and constructed to be compatible with the NTF. The material used is Nitronic 40. The Boeing Company has fabricated and successfully tested a two dimensional airfoil model in the 0.3 m TCT.

Studies on the overall model design problem for ETW, using Tornado as an example (fig. 11), have been performed by MBB and Dornier, considering different configurations and test conditions, model sizes, possible loads, sting deflections, accuracy requirements, surface finish and engine flows. The basic design of a 1:16.6 scale model for ETW has been carried out, considering several configurations.

The space available for balances of the NTF 101 and Able types, and for instrumentation has been examined. The distortion of the aft fuselage thought to be necessary by the sting dimensions is shown in Figure 12. The design of the wing (fig. 12) has also been pursued in some detail, including systems for remotely-adjusting the variable-sweep wings and for quickly-changing the flaps.

Studies on materials and joints have been performed at both companies and two steels (austenitic and maraging) have been selected as possible candidates. Both materials have been subjected to tensile testing at room temperature and at 77 K. The strength of maraging steels is greater than the strength of austenitic steels, but toughness decreases with decreasing temperature (see fig. 14). A reduced toughness increases the danger of fracture due to brittleness. Further examination of low-temperature properties of the selected steels has been carried out in the form of fatigue tests; the loads and the strains of a windtunnel model were simulated on notched test-specimens. The results obtained were compared with values from the literature and were used to calculate the theoretical life expectancy of windtunnel models in the cryogenic temperature range. These studies indicate that the fatigue life of a maraging steel model under buffet conditions may be rather limited. If the extremely highly-loaded model parts in a tunnel with a high stagnation pressure must be fabricated from maraging steel, because of high stress, there may be a lot of problems, including deformation, reduced workability after heat treatment, and long delivery times. Investigations of the temperature compatibility of components (constructional elements under static and dynamic loads, surface repairs, pressure orifices) are underway. Several miniature motors have been tested at 120 K for possible use as actuators; only a few have worked successfully.

The mean coefficients of expansion of epoxy resins with various proportions of fillers (glass micro-balloons, aluminum powder, graphite, silica, iron powder, clay) were measured to discover compounds compatible with metals in this respect. A dental cement was also examined. The shear strength of a joint between maraging steel cemented with Araldite loaded with glass micro-balloons was tested.

Three different adhesives have been tested at ambient and cryogenic temperatures by MBB and Dornier. Between temperatures of 70 - 270 K the adhesives investigated show a relatively high tensile shear strength: at temperatures higher than 270 K this strength is rapidly reduced.

It has been noted that the surface temperature of a composite model would approach the recovery temperature more quickly than one of steel. A RAE report [25] on use of carbon fibre in construction of models for conventional tunnels may be of interest though cryogenic applications were not considered. Wings with spans up to 760 mm were made: in one example it was noted that, in the case of a wing incorporating a large amount of instrumentation, a carbon fibre wing was stiffer in torsion though less still in bending than a corresponding solid steel wing with recesses.

5. INSTRUMENTATION

Instrumentation and measurement systems are important elements in any aerodynamic testing facility. However, the NTF, ETW and 4-CWT with their high pressure cryogenic test environments offer a greater challenge to instrument designers. The cryogenic environment requires that instruments either be developed capable of operating at cryogenic temperatures with high accuracy or be protected from the environment with controlled and conditioned enclosures.

To meet the challenges imposed by the high pressure cryogenic environment, a comprehensive development program was required. An expanded instrument research and development program for cryogenic application was begun at NASA Langley Research Center about five years ago and is still ongoing [36]. McDonnell Douglas has also been investigating instrumentation applications for their cryogenic blowdown facility 37. More recently, cryogenic instrumentation research programs have been initiated in Europe. Considerable progress has been made to date in most of the major instrumentation areas and a high degree of confidence exists that testing in the new facilities can be accomplished with the desired accuracy and response.

The remaining parts of this section will summarize the major ongoing instrumentation activities and highlight those areas where significant additional effort is required.

5.1 Force balances

The program at NASA Langley has centered around the one piece construction technique normally used at Langley for other facilities. Tests have been made utilizing heaters to control the balance temperature in the area of the bridges and also operating the balance at cryogenic temperatures [38-39]. A typical test balance is illustrated in Figure 15. The basic design of the cryogenic balance frame does not differ significantly from existing balances. However, when high stagnation pressures are required, the impact of the higher loads does require the balance to operate at higher stress levels. This is illustrated by the curves in Figure 16. The lower curve (dashed line) is respresentative of Langley conventional balances, the middle (solid line) and upper (dot-dash) curves represent the design conditions for the cryogenic six-component and three-component balances respectively. The consequence of these higher capacity balances will be larger deflections resulting in more critical and demanding calibration procedures and potentially high stress concentrations in the balance to sting attachment area. The three existing cryogenic balances have been successfully tested in the 0.3 m TCT.

The major problem in selecting material for balance construction was brittle fracture considerations, since in general, for the high grade maraging steels the strength tends to increase at the cryogenic temperatures. A criterion was established for the NTF that requires materials used for balances at low temperatures to have impact strength equal to balances used in existing ambient temperature tunnels. This criterion will insure that balance failures due to brittle fracture will not be a greater risk than for existing tunnels. The number of steels, however, that have both high yield strength and high impact strength at cryogenic temperatures is very limited. A survey of suitable materials and an in-house test program to confirm physical characteristics has been carried out. Based on this survey, NASA has selected Vascomax for NTF balances.

A comprehensive test program has been carried out to determine the best combination of strain gages, adhesive, solder, wiring and moisture-proofing for the selected balance material. This program was designed to define and minimize, where possible, the effects of the cryogenic environment on strain gage output when compared to its output at room temperature.

A Karma, SK-11, strain gage has been made to NASA specifications for the selected material. This gage with its self-temperature compensation factor of 11 minimizes the apparent strain output over the entire cryogenic temperature range. Also the change in gage factor of the SK-11 gage is most nearly equal and opposite to the change in modulus of the selected material, thereby minimizing sensitivity shift with temperature.

Various adhesives have been subjected to thermal shocks and large strain while the output was checked for evidence of permanent zero shifts or hysteresis under load. The selected epoxy-based adhesive that met these tests was M-610 a product of Micro-Measurements

Solder connections were subjected to a number of thermal cycles from 394K to 77K. Three of the solders tested maintained their electrical integrity throughout the tests. However, the solders containing antimony showed a tendency to become brittle and crystallize after long term cryogenic exposure. A solder containing 1.8 percent silver, 570-28R, did not exhibit this tendency. Therefore, 570-28R, marketed by Mirco-Measurements was selected for cryogenic balance application.

The wiring used for cryogenic application is silver-plated copper wire with teflon insulation. Tests have shown that it will be necessary to check all wiring junctions on cryogenic balances for thermocouple effects that can introduce errors in balance output.

A study of moisture proofing compounds is being carried out. A perfect moisture proofing compound for cryogenic application has not been located at this time. However, a compound, M-coat B marketed by Micro-Measurements, is being applied to exposed terminals with reasonable success.

In Europe, the major instrumentation concern for testing in cryogenic tunnels is force balances. Various small scale balances are being designed and constructed [40-42]. At NLR a 25 mm diameter three-component uninsulated balance is being constructed and tested (fig. 17). It is made from Vakumelt Ultrafort 301. Sixteen strain gages (SK-11-031 CF-350), six temperature sensors and ten thermocouples have been applied. The cement is M-bond 610 and the solder 570-28R, the same as at NASA. The protective coating used so far is a thin layer of M-bond 43-B. Provision has been made for heaters to be fitted but it has not been decided whether they will be used. Various supporting experiments on test pieces have been made and are reported in NLR information notes. There are plans for it to be tested in the 0.3 m TCT at NASA Langley in a cooperative program. At ONERA, a similar size balance is being developed and may be tested in the cryogenic tunnel T2 at ONERA/CERT. VFW is developing an unheated six-component balance of electron-beam-welded construction. An example under construction is 50 mm diameter with a normal force of 2000 N and the material is a maraging steel (Vacumelt Ultrafort 301, comparable to 18 Ni 1700). At DFVLR-AVA, Gottingen, an existing three-component balance has been regaged with Karma SK09 and TK06 gages and a six-component balance (diameter 30 mm, normal force 200 N) is being fabricated (fig. 18).

Although force balances maintained at normal temperatures would seem to have operational advantages, they are not being actively pursued in the USA or Europe at present. In Europe, the NLR balance is uninsulated and has provision for heaters, and at MBB a heated jacket for an existing Task balance has been designed and tested under cryogenic no-load conditions. Work at Oxford has raised the question of whether the heat flow out to the model surface via the model-to-balance joint will locally disturb the model surface adiabatic temperature. A lack of funds, together with the apparent confidence of NASA and NLR and others in the principle of a balance operating at cryogenic temperatures, has discouraged any further effort for the present.

5.2 Pressure measurements

Over the past five years the Electronically Scanned Pressure (ESP) Measuring System illustrated in Figure 19 has been developed at NASA's Langley Research Center with the primary objective being to satisfy the pressure measurement requirements of the NTF. The unique features of the ESP System are: high data rate (500 measurements per second); small size of sensor module (2.5 cm by 3.0 cm by 5.6 cm); one sensor per port; and the ability to perform in situ calibration. The system is capable of making a large number of pressure measurements almost simultaneously. The ESP System has undergone an extensive field evaluation and the overall results show that the ESP System can make measurements in a cold nitrogen environment to within 0.25 percent of full scale provided the module is contained in a temperature controlled enclosure and maintained at a constant temperature and the system is calibrated in situ immediately before each measurement. A development program is still underway to reduce the overall dimensions of the modules. Additionally, commercially available standard pressure instrumentation has been used very successfully with the NASA Langley 0.3 meter Transonic Cryogenic Tunnel.

In Europe, the work on pressure measurements in cryogenic tunnels falls into two classes. First, tests on individual transducers exposed to low temperatures in which it has been shown that some commercial transducers, though not all, survive without damage and without unacceptable changes in sensitivity although there are zero shifts. Those transducers of homogeneous construction appear to be least affected. Some work [43] on improving the temperature stability of semiconductor pressure transducers in England, though not directed towards cryogenic applications, may be relevant. Each transducer is backed by an analogue circuit which compensates for zero offset and sensitivity changes on the basis of the temperature of the transducer as measured by the resistance of its own bridge circuit. Adjustment of circuit values is necessary during calibration.

At ONERA/CERT [44] static pressure fluctuations on the walls of intermittent cryogenic tunnels have been measured using Kulite XCOL transducers whether mounted in a cavity in a small copper block (to minimize possible temperature gradients) or mounted in a brass block and connected to the pressure tapping by a short tube. Such transducer mountings have been used in cork insulation and frequency responses up to about 18k Hz are possible. Secondly, there are tests planned at various places (ONERA, NLR, DFVLR and Oxford University) on the electronically-scanned multiple-transducer systems (e.g. PSI, Scanivalve) recently developed in the USA. Such tests are aimed principally at familiarization with the techniques involved and are aimed initially at use in conventional windtunnels though they will be tried under cryogenic conditions in the future. In these cases it is clearly understood that temperature-controlled enclosures will be required.

5.3 Temperature Measurements

Experience with the NASA 0.3 meter Transonic Cryogenic Tunnel [45] has shown that temperature can be measured adequately with a combination of Platinum Resistance Thermometers (PRT) and thermocouples. A PRT can measure temperature with an uncertainty of less than 0.3 Kelvin. However, they have time constants on the order of two to three minutes. More rapid response can be obtained from thermocouples with some sacrifice in accuracy. An investigation carried out by NASA has indicated that careful selection of type T (copper-constantan) thermocouple wire can produce thermocouples with a high degree of repeatability, therefore, correctible to a high degree of accuracy. Typical results from calibration of these thermocouples are shown in Figure 20.

In Europe, temperature measurements in cryogenic tunnels have been made at Southampton and at CERT. At CERT tests have been made with thin-wire (0.1 and 0.2 mm) and thin-film thermocouples [46] (0.01 mm) and with thin-wire resistance thermometers (0.001 ahd 0.005 mm) (like conventional hot-wire probes but unheated) for measuring rapid temperature changes in the flow in small cryogenic tunnels. The thermocouples show a frequency response up to between 3 and 5 Hz according to size and the so called cold wires up to about 10 Hz. Experience [47] has indicated that the very thin wires (0.001 and 0.005 mm) are fragile at speeds above M = 0.2 and thicker wires (0.009 mm) have been used at higher speeds.

5.4 Model attitude measurements

The accurate measurement of model attitude is a problem common to all windtunnels using internally mounted strain gage balances from which aerodynamic forces and moments are resolved. The problem may be aggravated in the cryogenic high pressure tunnels due to the complication of the thermal environment on controlling temperature of inertial type devices and density effects on optical systems.

Two approaches to measuring model attitude in the NTF are being studied. First the conventional approach, which involves the use of precision accelerometers to detect the attitude of the model with respect to the local vertical is being studied. A sketch illustrating the approach is shown in Figure 21. There are two basic problems with this approach for the cryogenic application; first the slow response and second the large space required for packaging when insulation and heaters are provided. Because of these problems, NASA has been evaluating optical systems and selected one developed by the Boeing Company. This system is illustrated schematically in Figure 22.

The McDonnell Douglas Company in St. Louis, Missouri, is also developing an optical system for model attitude sensing. Status of this system was reported at the East Atlantic Meeting.

In Europe, ONERA has initiated a study [2] of methods for determining model attitude and deformation. Among them is the application of a device (Torsiometer BBT) employing a polarized beam from a 5mW helium-neon laser passing through a Faraday cell excited by 50 Hz alternating current and aimed at a small Scotchlite

reflector and thin analyzer (3-5 mm x 0.8 mm thick) on the model. The reflected beam is collected by a plane mirror (with a central hole for the incoming beam) and a lens and falls on a photo-electric detector. Such devices are in principle capable of high angular resolution (0.003°) but arrangements have to be made to follow the target on the model through pitch, yaw and roll. A laser-based device,[48] not using polarization optics, however, has recently been described for the measurement of model yaw and displacement in the RAE 5m low-speed tunnel. No other new activity in model deformation measurement has been reported in Europe.

5.5 Dynamic instrumentation

Tests have been performed in the Langley 0.3 meter Transonic Cryogenic Tunnel[49] to demonstrate the feasibility of using conventional root bending moment gages to determine buffet onset characteristics. The models used in the study and typical results are shown in Figures 23 and 24, respectively. The sharp edge delta wing, which was not expected to have a Reynolds number effect, was used to evaluate the effect of temperature on the test technique and excellent agreement was obtained between ambient and cryogenic temperatures. The data shown in Figure 18 illustrates the measured effect of Reynolds number on buffet onset for the NPL 9510 airfoil using the same technique.

Hot wire anemometry has been used to measure the flow dynamics at cryogenic tempratures in the 0.3 m TCT. Time varying measurements of velocity, density and total temperature were made. Wire breakage was generally worse than in other tunnels at the same dynamic pressure. This was attributed to a malfunction in the LN_2 injection system which resulted in larger than normal LN_2 droplets in the circuit. Additional tests are planned with improved LN_2 evaporation.

6. TEST TECHNIQUES

To utilize the new cryogenic tunnels to the maximum extent in understanding high Reynolds number flows, new techniques in the area of model deformation measurement, flow visualization and flow diagnostics must be developed. Model deformation measurement has been recognized as a problem in pressure tunnels for many years, however, the only systems in use today are passive stereo photographic systems requiring significant post test data workup. For the new high Reynolds number tunnels, the near real time model deformation system is deemed a requirement. Ideally, a continuous spatial definition in real time is desired, however, reality may force a compromise to a number of discrete points in near real time (i.e. a few minutes after test run).

Flow visualization techniques such as schlieren, shadowgraph and oil flow are in common use in conventional tunnels throughout the world. All of these techniques require additional development for application to the NTF and ETW.

Considerable progress has been made in the application of Laser-Doppler Velocimeters to windtunnel applications during the past ten years. All of the systems in use to date require some seed particles to be introduced in the air stream. Major problems that require solutions prior to utilization of these systems in the NTF and ETW have to do with seeding in the clean gaseous nitrogen stream and mechanical alighment of the hardware in the cryogenic environment. The ongoing activities and required work in these areas will be discussed in more detail in the succeeding parts of this section.

6.1 Model deformation measurement

NASA Langley has studied four optical concepts for model deformation measurements: (1) stero photo-grammetry, (2) scanning stereo photogrammetry, (3) moire topographic techniques, and (4) a microwave modulated light technique. All of these are well understood concepts and have been implemented in the laboratory. The difficulty, or problem to be solved, is one of implementing one or more of the techniques in a windtunnel environment.

The stereo photogrammetric technique[50] has been used in some windtunnels. It utilizes two or more cameras to view the object from different positions or angles. Given a number of fixed reference points, three dimensional motion can be extracted by noting the change in position of points on the object with respect to the reference points. The major shortcoming of this approach is the fact that it requires extensive data reduction after the fact.

The scanning photogrammetric technique is geometrically similiar to the previous approach but it provides real time or almost real time capability. Shown schematically in Figure 25, the system is programmed to rapidly scan a preselected array of points on the model. The major shortcoming of this approach is the requirement for active light source targets on the model. However, it appears to have the greatest potential for a near term solution, therefore, NASA is actively engaged in an effort to develop a system for the NTF.

The moire technique is also receiving some attention. It involves projecting a shadow grating onto an object and observing it with a TV camera. Subsequent electronic processing is employed to make vibration measurement, deformation and contour mapping. With the aid of high-speed digitizers and high speed, large capacity memories, multiple frames of video information can be obtained and some processing accommodated in real time. The concept is illustrated in Figure 26. In addition to providing real time data, this approach does not require any targets on the model surface. Therefore, it is felt to offer potential for a better long term solution than the scanning photogrammetry.

Another concept that has received some consideration is the microwave modulated light beam. This approach is illustrated in Figure 27 and utilizes fiber optic filaments routed to discrete points on the model and connected to a modulator inside the model. Using this system, a coherent variation in light is obtained from each point. Using one of the points as a reference, phase comparisons with the other points will provide an incremental measurement from which deformation information can be obtained. Several detectors or a scanning technique are required.

The reported work on model deformation measurement in Europe is entirely in France though this does not indicate a lack of awareness of the problem in the other countries. At ONERA, a study of the various possible methods has been undertaken. The methods include photogrammetry, photoelectric stereo optical detection from two stations using image dissector tubes and arrays of targets on the model, and pattern recognition in which an optical detector observes an array of targets on the model and then a computer searches for the best fit as a function of the geometry of the model and its attitude. Also at ONERA, a simple device has been used for wing trailing edge location or deflection measurement in connection with rake surveys using a pilot-tube rake. This method employs optical fibres (0.2 mm to 0.6 mm diameter) to conduct light to the wing trailing edge which is observed by an optical system in the rake support. Displacements of the trailing edge with respect to the rake give rise to an electrical output because of the movement of its image across a diaphragm in the optical system. It is suggested that two such systems could be used looking down into the top of a model for yaw measurement.

6.2 Flow visualization

Some work is underway at NASA to develop a suitable schlieren or shadow-graph system for the NTF. The facility design dictates that either of these systems must be located within the tunnel plenum chamber and thus the cryogenic environment. The problems of alignment, thermal effects on windows and other components are currently being investigated. In addition, a schlieren system has been designed and fabricated for the Langley 0.3 m TCT which will provide for direct facility testing and system evaluation.

Goodyer has demonstrated a surface flow visualization technique [51] in his small subsonic cryogenic tunnel at Southampton, England. The technique uses liquid propane as a carrier for a flourescent dye.

6.3 Flow diagnostics

A test of a one-component LV system has been made in the 0.3 m TCT [52] to investigate the potential for using residual LN_2 droplets as seeding. Typical results from this test are shown in Figure 28. The results are encouraging, although an analysis of the data suggests that a malfunction in the injection system had produced droplets too large for a high quality flow. Additional tests with a modified LN_2 injection system are planned.

6.4 Remote control manipulators

The idea of using remote control manipulators (such as used in atomic energy plants) for making minor adjustments to model in cryogenic tunnels without warming them up and providing a breathable atmosphere has been suggested at various times [53]. MBB in Germany has investigated [33] the possibilities in conjunction with a local manufacturer of such equipment and it has been shown (at room temperature in an unconfined space) that the replacement of simple parts such as wing slats retained by screws is possible. A film of the device in operation was shown at the meeting in Toulouse. Use of such devices will be considered in the final design of ETW. The concept is illustrated in Figure 29.

7 FLOW PHENOMENA

The original interest at Langley in minimum operating temperatures as established by the onset of condensation effects, has evolved into interest in two somewhat distinct condensation processes: effects resulting from the test gas forming its own nucleating site for droplet growth and effects resulting from growth on pre-existing nucleating sites (called "seed" particles). Concern about possible pre-existing seed particles in the test section flow has led to interest in the purity of the liquid nitrogen (LN_2) injected into the tunnel for cooling and in the completeness of its evaporation.

The first condensation process, that of self-nucleation of the gas, can be addressed by classical nucleation theory [54-56]. Uncertainties arise, however, because the theory usually requires an empirically determined constant [50-52]. For testing in transonic, cryogenic windtunnels, self-nucleation is most likely to occur in experiments where the local Mach numbers over the model exceed a value of 1.2 [57] because the higher the Mach number, potentially the greater the value of supercooling below the vapor pressure curve. The greater the supercooling, then the more likely self-nucleation is to occur. At Langley, the evaluation of onset temperatures has been with both airfoil pressure data and with some limited visual detection of the fog over the airfoil. A comparison between theoretical calculations by Sivier [55] and visually observed condensation onset is shown in Figure 30. The agreement between the observed onset of local fog over the airfoil and the theory is deceptively good as there were limitations to the experimental data and because the theoretical line was based on a curve fit to computer simulation of condensation in rapidly expanding hypersonic nozzles. Nevertheless, two important conclusions are that the onset of condensation effects occurred at the tunnel total temperatures above those corresponding to free-stream saturation and that classical nucleation theory appears to be able to predict the trend of the observed local effects. Additional airfoil data has been obtained and is currently under study. Further effort is also underway to program classical nucleation theory to simulate the onset of self-nucleation at expansion rates appropriate for transonic cryogenic tunnels.

Predicting the onset of effects due to the second condensation problem, that of growth occurring on pre-existing seed particles, depends on determining the size and number density of the seed particles that are being carried by the flow. While the onset of this type of effects in the Langley 0.3 m TCT has only been detected at tunnel total temperature, below free-stream saturation, there is no fundamental reason why this may not occur at temperatures higher than free-stream but below local saturation. Until now, the investigation of the seed particles has centered on analyzing differences in total pressure measurements down the length of the 0.3 meter test section. The intent of the analysis is to see if a hypothesized number and size of seed particles can result in the type of total pressure losses detected during experiments. There are at least two possible sources of seed particles in cryogenic tunnels--impurities carried into the tunnel with the injected LN_2 and unevaporated droplets remaining in the flow because of incomplete evaporation of the injected LN_2. This second source of seed particles can be a limiting factor in the low temperature operation if the LN_2 injection system is not efficient over both the Mach number and the total pressure ranges.

In summary, condensation effects can take place over a test model because of either self-nucleation of the test gas or because of condensation on pre-existing seed particles. During experiments in the 0.3 m TCT, self-nucleation has been observed at tunnel temperatures below local, but above free-stream saturation. While effects due to seed particles have not been observed above free-stream saturation temperature, there is no reason why this may not occur locally.

In Europe, theoretical and experimental studies on the estimation of simulation errors and possibilities of operating temperature range extensions for ETW [2] are being conducted jointly at DFVLR Gottingen [58] and Dornier. The work can be divided into two areas: (1) theoretical investigations into the influence of real gas effects and heat transfer on turbulent shock wave-boundary layer interactions, and (2) theoretical and experimental studies on condensation effects on nozzle and profile flows. The experimental work is being performed in an apparatus modified from a low density windtunnel to simulate, in a nozzle, the pressure variation over the airfoil surface.

7.1 Real gas effects on flow simulation

Early in the development of cryogenic windtunnels, it was realized that nitrogen, the prime cnadidate test gas, departs from the ideal gas constant specific heat model at cryogenic temperatures. A program was undertaken by Adcock at Langley with support of the National Bureau of Standards (NBS) to: (1) examine the adequacy of existing math models for cryogenic nitrogen gas, and (2) compare the different kinds of flow solutions with those for the ideal-diatomic, constant specific heat gas.

In the area of math models (equation of state), the NBS indicated that the multi-term equation by Jacobsen [59] was the best fit to existing nitrogen property data. The NBS was contracted, by Langley, to obtain additional speed of sound data in the temperature and pressure range of the 0.3 m TCT and the NTF and to refit the property data with emphasis on this range [60]. A comparison of the thermodynamic properties and simple flow properties (figs. 31 and 32) predicted by the three prime equations of state (Jacobsen, NBS-NASA, and Beattie-Bridgman) with those predicted by the Van der Waals equation leads to the following conclusions: (1) the superiority of any of the prime equations would be difficult to prove, (2) the differences in uncertainties in the value of the various properties, and (3) the differences in simple flow parameters given by the three prime equations are not significant when compared to the magnitude of the deviations from the real gas parameters. As a result of this analysis, NASA Langley utilizes the Beattie-Bridgman equation of state in its cryogenic tunnel data reduction programs because of its relative simplicity.

Real gas effects have been analyzed for a variety of different flow types including inviscid, normal-shock, boundary layer flows. The published work [61-63], primarily for one-dimensional isentropic flow, has indicated that gaseous nitrogen is a valid test medium at least down to free-stream saturation. If future condensation studies indicate that windtunnel operation at temperatures several degrees below free-stream saturation conditions at high pressures (5 to 9 stmospheres) is feasible, then a more detailed look at real gas effects under these conditions is required.

Some research has also been done at NASA Langley [64-65] on the simulation of boundary layer parameters in cryogenic gaseous nitrogen. This analysis covers laminar, turbulent, adiabatic and non-adiabatic boundary layers. No significant deviations from the ideal gas solution have been seen.

The one area that has received very little attention in the simulation analysis is that of viscid-inviscid interactions. Since neither the viscous or inviscous flows are appreciably affected by real gas effects, it is not anticipated that the interaction will be appreciably different than the ideal gas case, but it is an area that may require additional research.

7.2 Wall temperature ratio

The possible magnitude of errors in measurements due to adiabatic wall temperature ratio differences from unity have been discussed by Green and others [66-67]. It is their view that the average surface temperature of the model should be within one percent of the adiabatic recovery temperature with a maximum local excursion of two percent. If this is difficult to achieve perhaps twice these values could be accepted in which case the spurious effects of heat transfer might be the largest sources of error in the results (assuming no problems in other areas such as balance performance or flow quality). The demand for one percent mean error in wall temperature follows from requiring less than 0.5 percent error in wing drag.

The impact of the suggested criteria on the windtunnel projects in the USA and Europe has been actively examined. The model has to be temperature-conditioned either before, or during the first part of the run. Experience has shown that there are technical difficulties in preconditioning models mad of low-conductivity steels; some experiments to investigate these problems are being planned at Oxford. NASA papers [68-69] have given useful estimates of the times required for the surface temperatures of parts of typical models to come within reasonable limits. Experimental checks on the recovery temperatures attained in practical have been made at NASA [65], and at CERT the effect of wall temperature ratio on the measurements of lift and drag has been examined [70] by testing an initially-warm two-dimensional model in the ambient temperature tunnel T2 (now converted for cryogenic operation).

At Oxford University, some work has been done on the heat transfer environment of a strain gage balance in a model [71]. This has led to some conclusions on the effect of a heated balance on the model surface temperature distribution.

7.3 Liqud nitrogen injection

Investigations in the Langley 0.3 m TCT have indicated that a uniform temperature distribution in the test section is not extremely sensitive to the location or technique for nitrogen injection [4]. Additionally, provisions have been made in the 0.3 m TCT for measurement of LN_2 droplet size at various points in the tunnel circuit. These measurements will be used to study the evaporation process.

In Europe, liquid nitrogen injection studies have been made at CERT and ENSAE. At CERT, the tests [72] have included studies of temperature distributions across the pilot tunnel T2 and the effects of nitrogen injection on the temperature and pressure fluctuations in the circuit. At ENSAE, a method has been developed for measuring the size distribution of liquid nitrogen droplets in a stream of gaseous nitrogen [73].

8. CONCLUDING REMARKS

The feasibility of using cryogenic windtunnels has been well established and a considerable amount of research on test technology for cryogenic application has been accomplished and is continuing. Before the confidence level of the user community reaches that associated with existing ambient temperature tunnels however, much additional operating experience will have to be gained, particularly with regard to large three-dimensional models, along with additional research on test technology in selected areas.

In the general discussion, during, and at the end of the meeting in the United States, the major areas of concern were practical problems associated with model fabrication, instrumentation, location of boundary layer transition and wall temperature effects.

Some of the model and instrumentation areas where significant additional effort is required and studies should be initiated are:

Models

- o Filler materials to allow quick model modifications comparable to conventional tunnels.
- o Use of dissimilar materials.
- o Installation of a large number of wing pressure taps (300 plus).
- o Fabrication of very smooth surfaces.
- o Large sting design sizes dictated by divergence considerations.
- o Impact of rapid temperature changes.
- o Potential for using composite materials.
- o Machinability of some of the high strength materials.

Instrumentation

- o Effect of temperature gradients on balances.
- o Flow through balances for propulsion testing.
- o Hinge moment measurements.
- o Establishment of optimum pressure tube length.
- o Cryogenic stripper tubing.
- o Angle-of-attack and model deformation measurements.
- o Transition detection.
- o Overall reliability of instrumentation in cryogenic environment.

During the East Atlantic Meeting in Toulouse the main areas of discussion were:

- o Model design and construction.
- o Force balances.
- o Model wall temperature effects.
- o Balance to model heat transfer effects.
- o Condensation and real gas effects.
- o Materials.
- o Manipulators for remote model adjustments
- o Sting size and divergence characteristics.

Several areas were identified and discussed, where cooperative programs were considered to have a high probability of benefit to all parties. These included: (1) force balances, (2) condensation effects, (3) heat transfer environment of models and balances, and (4) model deformation measurements. It was suggested, and seemed appropriate, that the best media for exchange would be: (1) small working meetings of specialists, rather than large general meetings which require considerable preparation and travel budgets, (2) cooperative research programs with joint participation in the experiments, and (3) exchange tours of duty between researchers in the various research establishments.

The possibility of specialists meeting on force balances to be held in the United States, and model deformation to be held in Europe were discussed. It appeared from the material presented that there is sufficient activity and diversification of effort to make additional working meetings in these areas worthwhile; however, no definite plans were made. In addition, it is believed that specialist meetings would be beneficial on model design and construction and the heat transfer environment of models and balances. Although the efforts in these areas, on each side of the Atlantic, are different at this stage, they are in some respects complementary. It is proposed that discussions should continue between the conveners to explore the possibility of arranging such specialist meetings at some time in the future. Examples of current cooperative programs include tests of a NLR designed balance in the Langley 0.3 m TCT as part of the NASA-AGARD cryogenic technology exchange agreement and the assignment of Dr. Venneman of the DFVLR to conduct basic research on minimum operating temperatures with Dr. Hall of Langley.

9. RECOMMENDATIONS

In the future, it is not clear that the convener activity should take the same form as it has so far. Since the NTF will begin operations in the United States during the latter part of 1982, it will naturally be the focal point for cryogenic testing technology in the United States. A close working relationship and technical exchange with the U.S. aerospace and university communities is planned through regular workshops and conferences as partial fulfillment of NASA's responsibility for NTF operation. Additionally, active participation in technical societies such as the American Institute for Aeronautics and Astronautics (AIAA) and the Supersonic Tunnels Association (STA) is planned. In Europe the ETW project will arrange regular cryogenic technology information meetings in the future making special convener meetings superfluous. In view of these considerations the following recommendations are made:

1. Continue the exchange program on fundamental cryogenic technology now existing through the Fluid Dynamics Panel between NASA and the ETW technical group.

2. The Fluid Dynamics Panel sponsor small working meetings, on an international basis, in specific areas such as model deformation and model wall temperature effects.

3. Encourage joint research programs and exchange tours of duty between researchers in areas of mutual interest and benefit.

4. Cancel the second East and West Atlantic meetings as originally proposed and arrange attendance by the opposite conveners at suitable meetings on each side of the Atlantic. As regards the East Atlantic meeting this could be close to a regular meeting of the Fluid Dynamics Panel and include a report on U.S. activities by the NASA Langley member of the Fluid Dynamics Panel.

5. The Fluid Dynamics Panel sponsor an international symposium or conference on cryogenic testing technology in the late 1983 or early 1984 time period and encourage the broadest participation possible.

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LOCATION	TUNNEL NAME	MAX. PRESS. (BAR)	RUN DURATION	TEST SECTION HEIGHT X WIDTH (m)	DRIVE	INSULATION CONCEPT	REMARKS
NASA LANGLEY RESEARCH CENTER	NTF	9	CONTINUOUS	2.5 x 2.5	FAN	INTERNAL	COMPLETION MID 1982
	0.3 MTCT	6	CONTINUOUS	0.61 x 0.20	FAN	EXTERNAL	ORIGINAL PILOT CRYOGENIC TUNNEL CONVERTED TO RESEARCH FACILITY IN 1976
DOUGLAS AIRCRAFT CO. EL SEGUNDO CALIF.	DAC 4 CWT	4	20 SECONDS	1.22 x 1.22	BLOW DOWN	INTERNAL	FIRST RUN LATE 1980

TABLE 1-A MAJOR U.S. CRYOGENIC WIND TUNNELS

LOCATION	TUNNEL NAME	MAX. PRESS. (BAR)	RUN DURATION	TEST SECTION HEIGHT X WIDTH (m)	DRIVE	INSULATION CONCEPT	REMARKS
ONERA/CERT	T'2		30 - 40 SECONDS	0.1 × 0.1	INDUCED-FLOW	INTERNAL	1:4 SCALE VERSION OF T2
	T2	5	30 - 60 SECONDS	0.4 × 0.4	INDUCED-FLOW	INTERNAL	
	T'3	3	SEVERAL MINUTES	0.15 × 0.1	FAN	INTERNAL	
ENSAE		4		0.35 × 0.15	FAN	EXTERNAL	
NLR AMSTERDAM	PETW	4.5	ABOUT 10 MINUTES	0.23 × 0.27	FAN	EXTERNAL	1:8.8 SCALE PILOT TUNNEL FOR ETW COMPL: MID-1982
UNIVERSITY OF SOUTHAMPTON		1	ABOUT 10 MINUTES	0.1 × 0.1	FAN	EXTERNAL	
DFVLR	KKK	1	ABOUT 12 MINUTES	2.4 × 2.4	FAN	INTERNAL	MODIFICATION OF EXISTING CONCRETE LOW SPEED TUNNEL (V = 100m/s)

TABLE 1-B EUROPEAN CRYOGENIC TUNNELS: EXISTING AND PLANNED

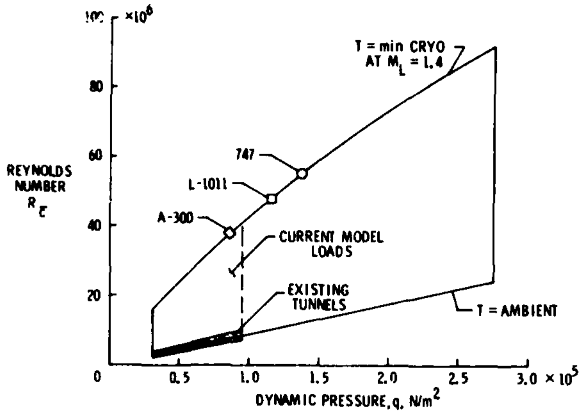


Figure 1.- NTF operating envelope at M=0.3 for typical transport models. Model span = 1.5 meters.

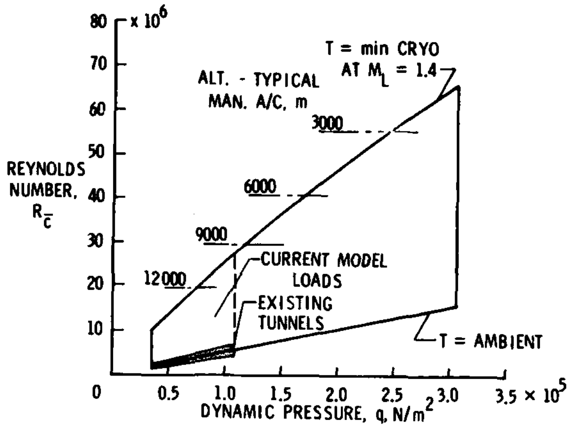


Figure 2.- NTF operating envelope at M=0.9 for a typical fighter model. $\bar{c}$=14.2 cm.

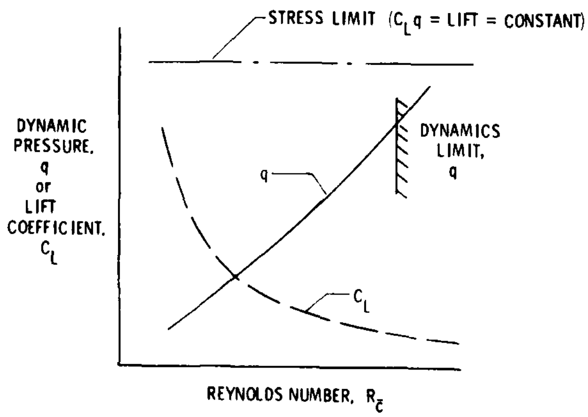


Figure 3.- Model imposed limits on matching aircraft flight conditions.

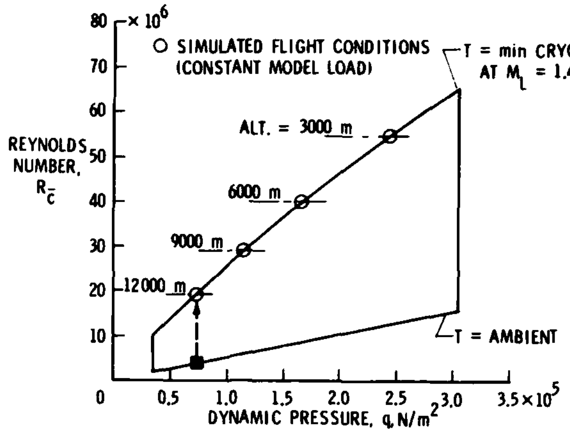


Figure 4.- NTF operating envelope at M=0.9 for a typical fighter model $\bar{c}$=14.2 cm.

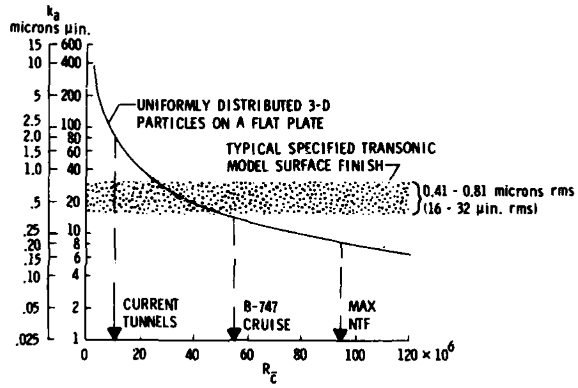


Figure 5.- Admissible roughness (k_a) for typical NTF sized models. $\bar{c}$=0.20 meters.

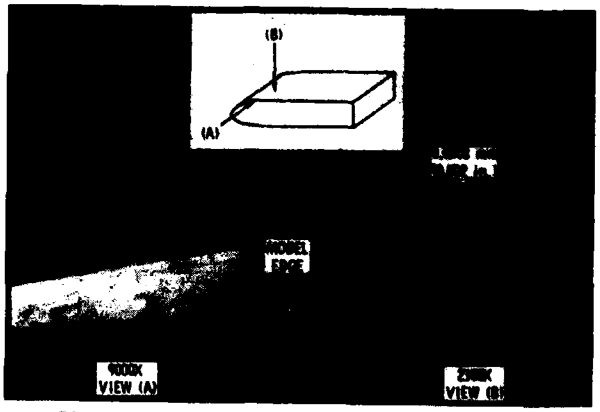


Figure 6.- Electron micrographs of a typical model surface finish. 0.2-0.3 microns rms as measured by a stylus.

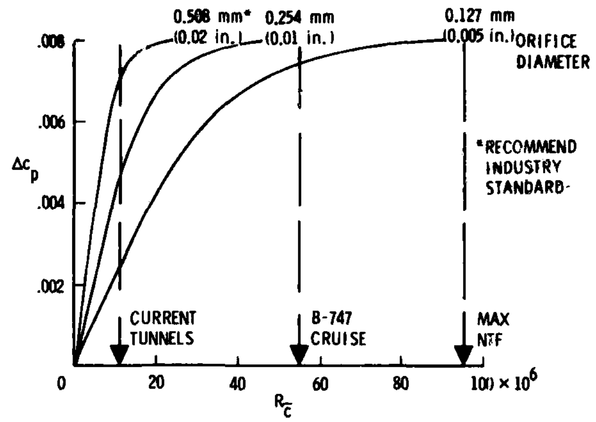


Figure 7.- Orifice induced pressure error for typical transport model. c̄=0.20.

MATERIAL	CONDITION	σ_{yp}, MPa		σ_u, MPa		CVN, J		K_{Ic}, MPa-m$^{1/2}$	
		300K	78K	300K	78K	300K	78K	300K	78K
18 Ni STEEL	250	1724	2206	1793	2275	27.1	13.6	110	44
18 Ni STEEL	200	1413	1862	1448	1931	47.5	33.9	187	88
AF 1410 STEEL	DOUBLE AUSTENITIZED AND AGED	1586	1724	1724	1793	54.2	40.7	138	--
SPECIAL 9% Ni STEEL	NORMALIZED & TEMPERED QUENCHED & TEMPERED STRESS RELIEVED	724	1000	793	1207	--	108.5	--	176
A286 STAINLESS STEEL	SOLUTION TREATED AND AGED	689	827	1103	1482	74.6	67.8	132	121
NITRONIC 40 STAINLESS STEEL	ANNEALED	483	1034	758	1379	271.2	88.1	--	182
PH 13-8 Mo STAINLESS STEEL	H1150M	586	1000	896	1207	108.5	81.3	--	--
INVAR	ANNEALED	276	621	552	862	298.3	67.8	--	--
INCONEL 718	SOLUTION TREATED AND AGED	1034	1207	1276	1620	27.1	27.1	90	110
INCONEL X750	SOLUTION TREATED AND AGED	758	862	1241	1482	47.5	47.5	--	110
Ti-6Al-4V ELI	ANNEALED	896	1310	931	1413	27.1	13.6	90	61
Ti-5Al-2.5Sn ELI	ANNEALED	724	1207	827	1241	33.9	13.6	90	72

Figure 8.- Nominal tensile and toughness properties of material considered for NTF models.

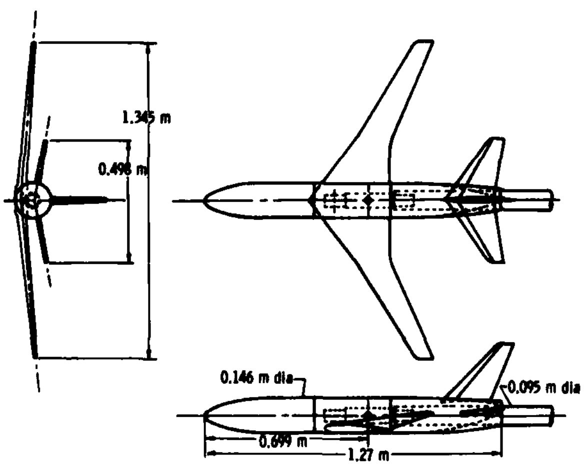


Figure 9.- Transport model.

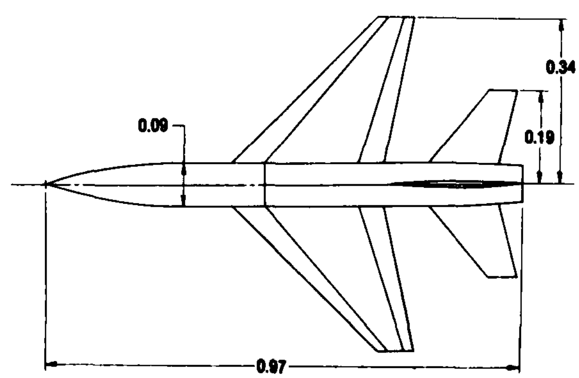


Figure 10.- Generalized maneuvering aircraft model.

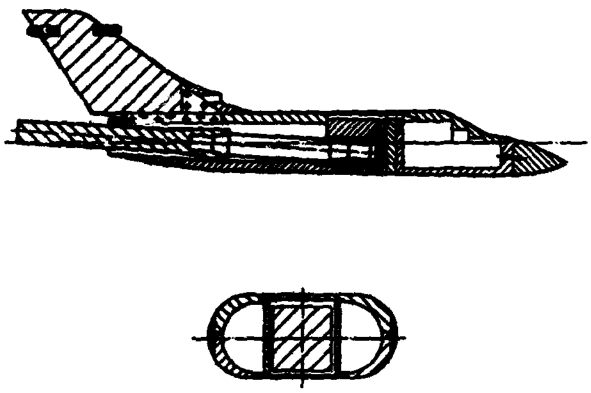


Figure 11.- Tornado model showing sting section.

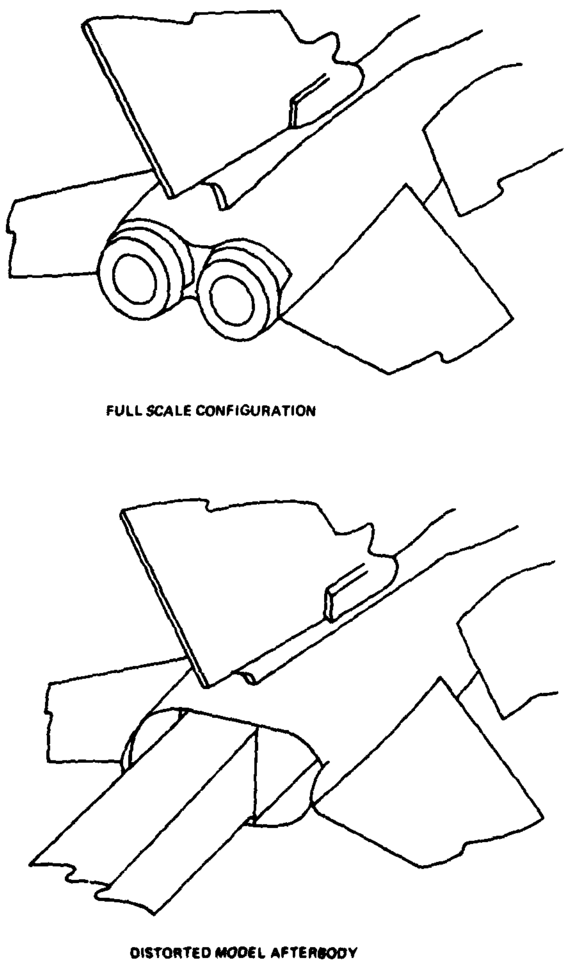


Figure 12.- Distorted afterbody on tornado model.

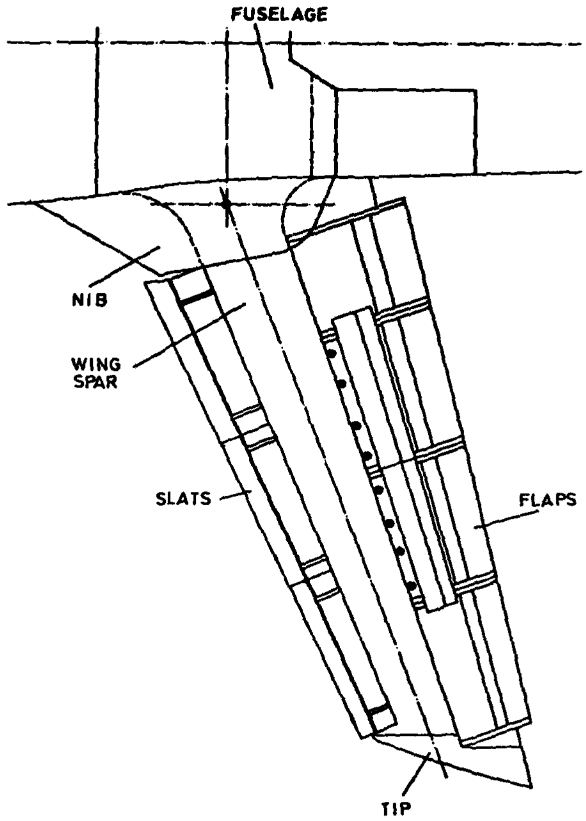
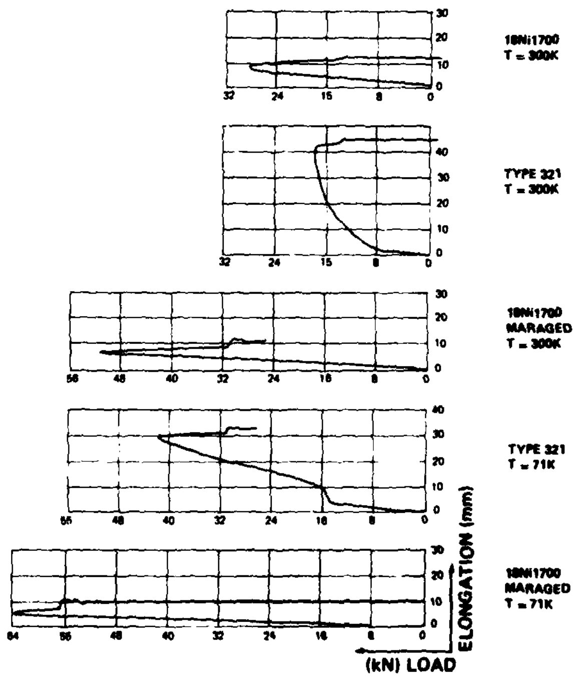


Figure 13. - Tornado wing system



TENSILE PROPERTIES OF STEELS FOR MODEL CONSTRUCTION
18Ni1700 (MARAGING) AND TYPE 321 (AUSTENITIC)

Figure 14. - Tensile properties of some steels considered for ETW model construction. 18 Ni 1700 (maraging) and type 321 (Austenitic).

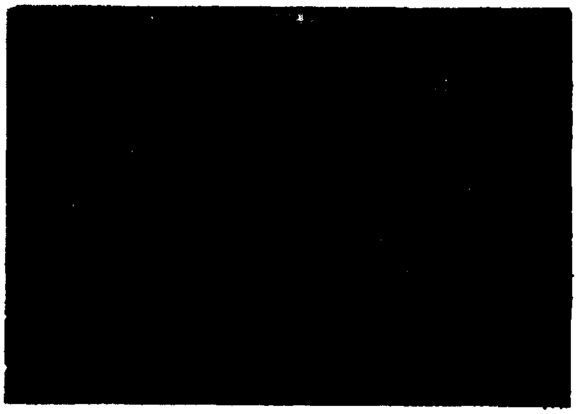


Figure 15. - Evaluation balance HRC-2.

Figure 19. - Thirty-two (32) channel electronically-scanned pressure sensor module.

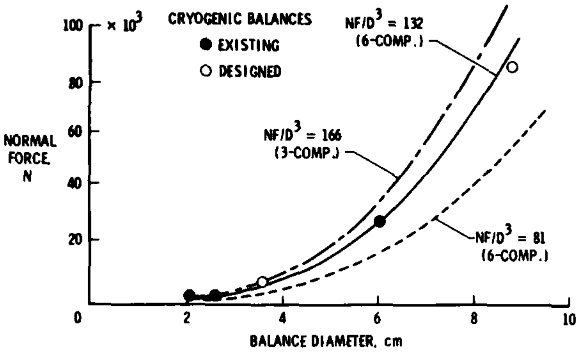


Figure 16. - *Relationship between balance* normal force capability (NF) and diameter (D).

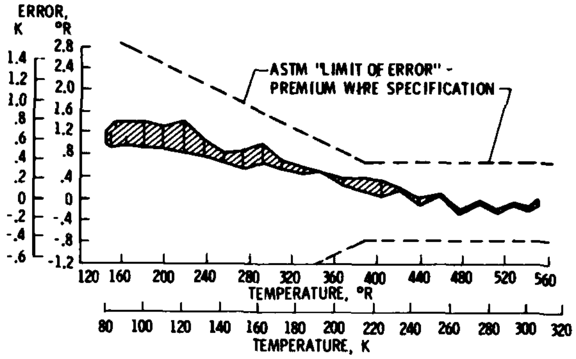
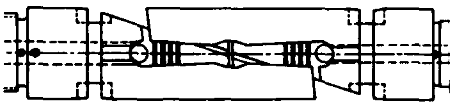


Figure 20. - Results of the calibration of four (4) type T thermocouples.



CENTER SECTION OF 25mm DIAMETER NLR FORCE BALANCE

Figure 17. - Center section of 25 mm. diameter NLR force balance.

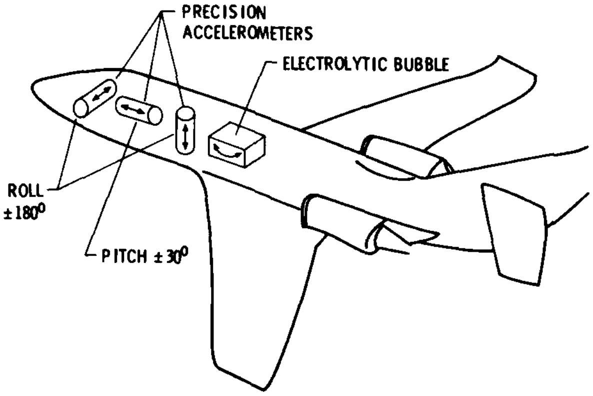
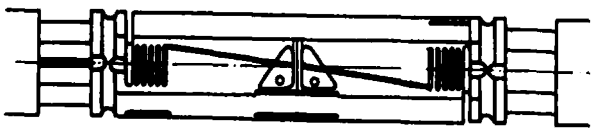


Figure 21.- Illustration of inertial devices in an NTF model.



CENTER SECTION OF 30mm DIAMETER DFVLR FORCE BALANCE

Figure 18. - Center section of 30 mm. diameter DFVLR force balance

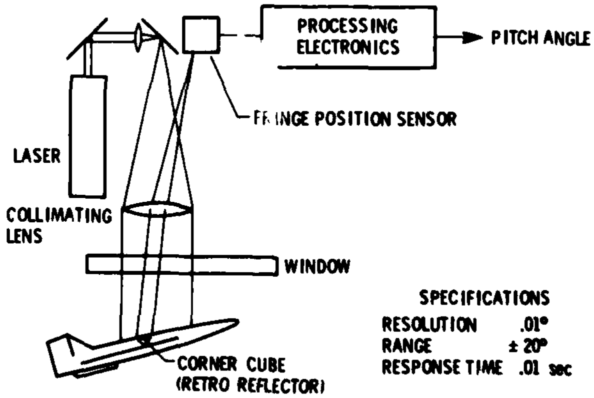


Figure 22.- An optical pitch angle sensor.

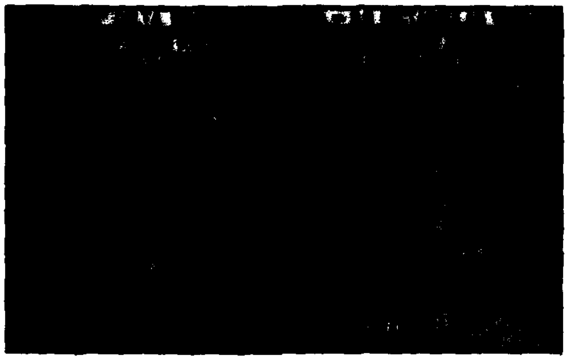


Figure 23.- Photograph of buffet models.

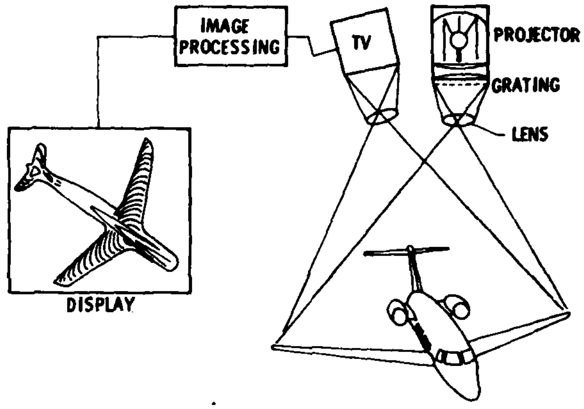


Figure 26.- Moire topography.

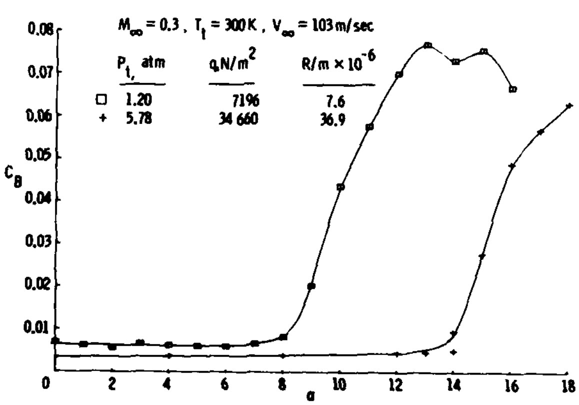


Figure 24.- Buffet data for NPL-9510 airfoil.

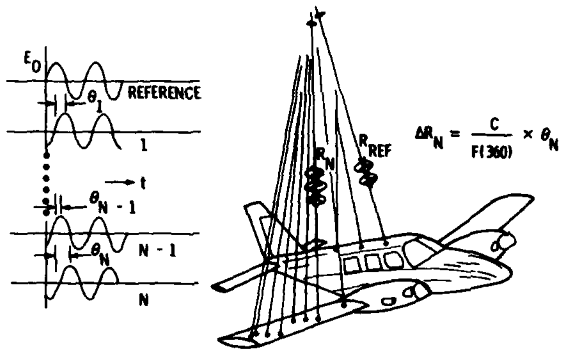


Figure 27.- Microwave modulated light beam.

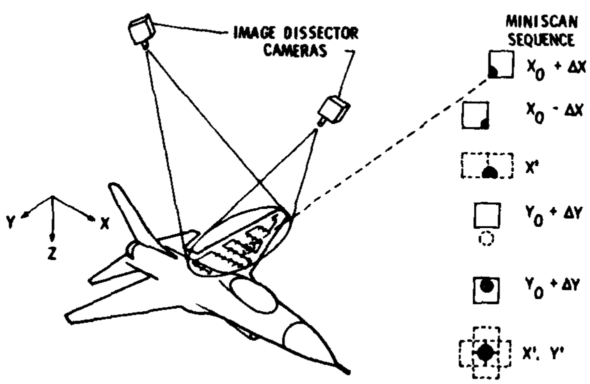


Figure 25.- Scanning stereo photogrammetry.

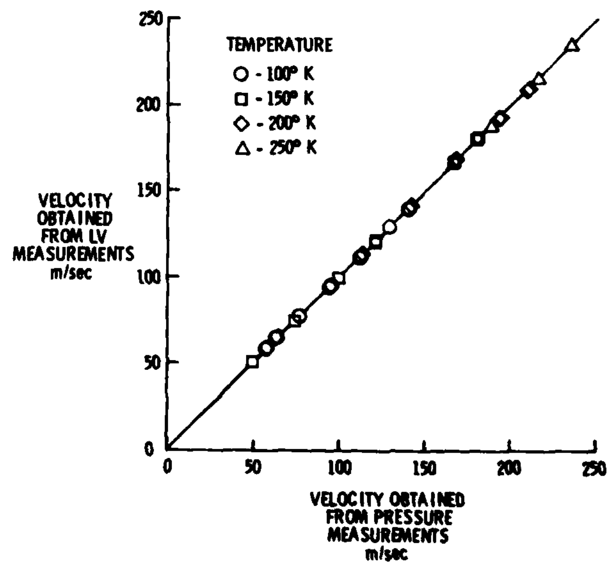


Figure 28.- Comparison of velocity measurements in 0.3 m. TCT by laser velocimeter and static pressure gages.

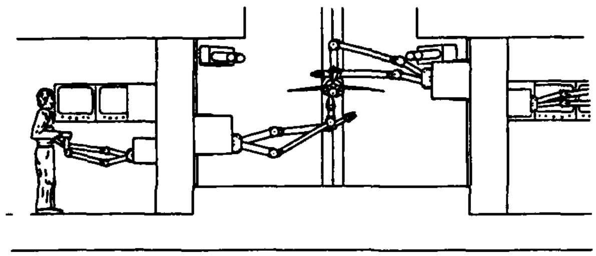


Figure 29.- Artist's impression of a manipulator in use to change model configuration in the ETW.

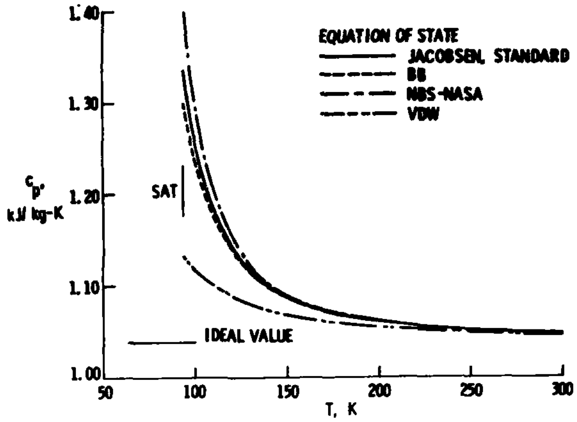


Figure 31.- Specific heat at constant pressure, C_p, for nitrogen gas at P=5 atm, "SAT" denotes saturation temperature. The Jacobsen line is taken to be the accepted value.

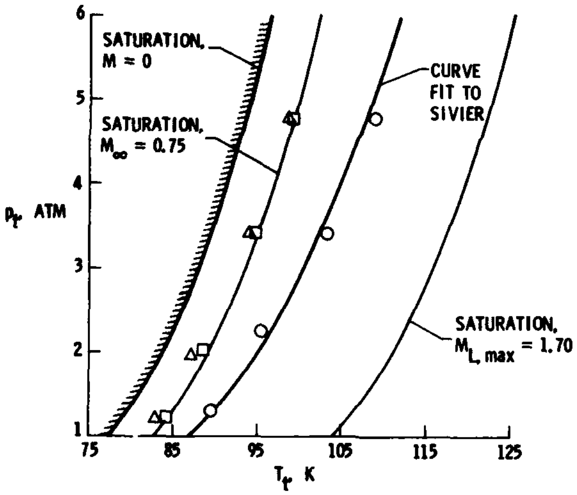


Figure 30.- Onset of condensation effects for NPL-9510 airfoil. M=0.75, α=6 degrees, M_L=1.70

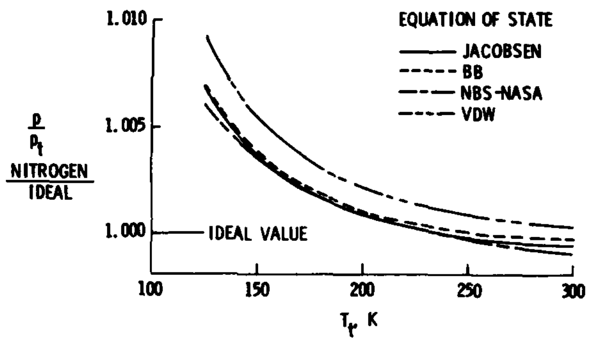


Figure 32.- Isentropic expansion ratios for nitrogen expanded to M=1.5 at P=9.0 atm.

APPENDIX 3

REPORT OF THE CONVENERS GROUP ON INTEGRATION OF COMPUTERS AND WIND TUNNEL TESTING

by

M.C.P.Firmin
Aerodynamics Department
Royal Aircraft Establishment
Farnborough, Hants GU14 6TD, UK

and

J.L.Potter
Arnold Engineering Development Center
Arnold Air Force Station, Tennessee 37389, USA

Edited by
J.E.Green
Ministry of Defence PE
St.Giles Court
1 St.Giles High Street, London WC2 LD, UK

SUMMARY

This Conveners' report is based upon contributions, from experts in the subject, made at one of the following meetings:

1. Western Atlantic meeting, held at Hilton Inn, Chattanooga, Tennessee, on 24 and 25 September 1980;

2. Eastern Atlantic meeting, held at RAE Bedford, UK, on 18 and 19 February 1981.

Fifty-five specialists gathered together at the meeting in Chattanooga, and thirty-six gathered at the comparable meeting in Bedford. Participants attended from research organisations, Industry and Universities. Both Conveners attended both meetings.

The statements and conclusions are, in the opinion of the authors, representative of the views expressed at the time, or put forward in the written contributions which are listed at the end of this report. Copies of the contributions, which are listed in the Annex, are available from the respective authors.

1 INTRODUCTION

On both sides of the Atlantic a considerable investment is being made in the advance of computational fluid dynamics (CFD) and in the improvement of wind tunnel test capability. The complementary roles of CFD and the wind tunnel, and their growing interdependence, are becoming universally recognised. One aim of the Conveners' Group has been to foster a more rapid development of links between the two fields than might occur if the wind tunnel and CFD specialists were left to their own devices.

The discussions in the Conveners' Group were restricted to specific issues, which were defined in advance by TES.

The purpose of the Group was to provide a forum for the exchange of ideas and information on current work, and to act as a stimulus for new work, bearing on the following items.

(1) The possibility of achieving more efficient use of tunnel time through interactive use of real-time, non-CFD computation with variation of model configuration, attitude, and tunnel test conditions.

(2) The use of CFD to correct wind tunnel data (*eg* for wall constraint, aeroelastic distortion, incorrect engine simulation) and to extrapolate to full-scale Reynolds number.

(3) The role of wind tunnel testing in critical assessment of CFD codes and the fluid dynamic modelling built into them. In particular, the need for benchmark test data and the design of experiments to provide them.

(4) The use of CFD as a guide during wind tunnel testing to enable more efficient use of tunnel time. The possibilities for interactive use of CFD and wind tunnel.

The following were *not* to be considered by the Conveners' Group:

(i) Development of CFD *per se*.

(ii) Improvement in wind tunnel testing and techniques not involving CFD.

(iii) The non-interactive use of real-time, non-CFD computation for:
- (a) wind tunnel and model control;
- (b) data acquisition and display;
- (c) control of specialised measuring techniques.

(iv) The role of computation in the closed-loop control of adaptive walls (this being the province of the Conveners' Group on Transonic Test Sections).

The term CFD for our purposes was taken to mean numerical solutions of the equations of fluid motion, as distinct from more empirical treatments.

This report considers each of the four items in turn, reviews the work presented at the meetings, discusses the goals and plans for future work and, where appropriate, makes recommendations for future cooperation.

2 EFFICIENCY IN TEST UNIT OPERATIONS THROUGH USE OF INTERACTIVE, 'REAL-TIME' COMPUTATION

This section concerns interactive uses of computers in conjunction with test unit operations, excluding any computational fluid dynamics (CFD) applications. It will be recognised that such computer usage is relatively widespread and growing because it makes possible savings in time and energy as well as improvements in accuracy and safety. Furthermore, it is apparent that a significant number of new test techniques simply would not be feasible without on-line use of computers for data processing and test unit control. The use of computers merely to save time in plant control and data processing was not of primary concern in the Conveners' meetings reported herein, because such uses are well developed and understood. Interest was focussed on integrated, interactive, relatively advanced applications. The definition of the term 'interactive' is here taken to mean that test unit and computer are linked so that output from one is acted upon by the other and signals are passed in each direction for controlling the process. One may argue that having a human in the loop does not disqualify the system as an example of interactive use. For example, if a computer is called on to compute the predicted model response to test conditions so as to guide the testing in a near real-time manner, and if a human decision-maker effects the interaction, then is it or isn't it an interactive application? Some examples of this type are reported because they do represent the state of the art.

2.1 Reports on work underway

Contributions 1-7 at the end of this report give examples which were described at the two Conveners' meetings reported herein. Brief comments on this work follow.

2.2 Interactive engine testing at the AEDC-ETF (Contribution 1)

At the Engine Test Facility of the Arnold Engineering Development Center (AEDC), real-time computation is used for data monitoring. This includes comparison of engine mathematical model and measurement results, as well as on-line test point selection. The air-jet system used to produce distorted airflow profiles at engine inlets is computer controlled, with cathode ray tube (CRT) display provided for examination by the test engineers.

Transient engine testing may or may not be considered an example of interactive computer usage, depending on what constitutes interaction. Data processing, plant control, data analysis and correction all involve computer use. However, some of the decision-making on the basis of computer and test unit outputs is automatic and some is done by the test engineers.

2.3 Interactive compressor testing at MIT (Contribution 2)

At the Massachusetts Institute of Technology computer-aided data collection, analysis, and test unit control have made it possible to conduct compressor testing in a blowdown tunnel with 40-50 ms useful test time. A period such as that is so brief that real-time human response to the data is impossible. However, the capability to produce computer-drawn charts of several hundred thousand data samples within 30-40 minutes after a test is near enough to real time to allow some examination of the results before the tunnel can be readied for another run. That capability exists because of a sophisticated, computerised data system with extensive software.

The MIT blowdown facility has been described in some detail in Ref 1. The facility consists of: a supply tank, initially separated from the compressor by a diaphragm; a compressor test section; and a dump tank into which the compressor discharges. The test section and dump tank are initially in vacuum. This allows the rotor to be brought to speed with only a few horsepower. When the diaphragm ruptures, the gas expands from the supply tank (which acts essentially as a stagnation plenum). The axial Mach number is established by an orifice downstream of the rotor. As the supply gas expands its pressure and temperature decrease, but the rotor (driven only by its own momentum) slows since it is doing work on the flow. By proper matching, the tangential Mach number and thus the inlet angles to the rotor can be made constant through the test time. The time during which the flow angles are well matched is 40-50 ms.

2.4 Interactive wind tunnel testing: NASA Marshall (Contribution 3)

Wind tunnel tests conducted to determine sound pressure levels at the base of the NASA Space Shuttle Solid Rocket Booster (SRB) provide another example of interactive computer use. Tests were conducted of a scale model of high fidelity in its representation of the full-scale SRB configuration. It was desired to ascertain maximum flight sound pressure levels at various locations, the Mach number and SRB attitude where these occurred, and the frequencies of the unsteady pressures. A mini-computer read the digital output of the transducers and their rms detector system. For spectral data, the amplified

transducer signals were switched by the computer to an analyser and the outputs finally read by the computer. Signals from all transducers were tape recorded. The computer started and stopped the tape recorders, handled dc calibrations of the transducers, initiated and stopped model mounting sector steps, read sector position, calculated tunnel flow conditions and printed and stored all such information. The computer was programmed to analyse test data and select those conditions where detailed spectral data were to be acquired.

2.5 Supportive computations during testing at AEDC (Contributions 1, 4, 5)

It has become possible to provide computed results for use in guidance or verification during testing. These computations are, at present, of the non-CFD variety, but when more powerful computers are available it will be possible to include simpler forms of CFD support during testing. Therefore, this work is the forerunner of the advanced integration expected to evolve in the future.

Examples described in the Conveners' meetings included engine mathematical model computations routinely provided during air-breathing engine tests at the AEDC Engine Test Facility.

Mathematical model applications range from pre-test preparations to post-test applications. Pre-test activities include sizing and design of test hardware, training of test facility operators on facility simulators, and selection of test conditions. Test activities include control of test functions with mathematical models in the control loop, on-line data verification and comparisons of model to experimental results to guide the test program. Post-test applications include data validation, analysis, adjustment for test induced effects and test article mathematical model validation. Further post-test uses include support to flight test programs and field problem resolution. The verified mathematical model also provides a compact store house of accumulated knowledge which may be used to guide new propulsion system developments.

Mathematical model adjustment of engine test data to reduce test time is illustrated by the ETF Short Duration Turbine Engine Testing technique (SDTET). With SDTET, engine data are acquired in a slow power transient mode, and adjustments for transient effects are made using mathematical models to yield the steady-state results in a fraction of the time consumed in normal steady-state testing.

Mathematical model extension of compressor surge data from the as-tested situation where one parameter is held constant to a condition where another parameter is constant is accomplished by application of a compressor mathematical model which has been verified through experimentation.

If he wishes to compare test data with computed predictions for a missile model being tested, an AEDC propulsion wind tunnel engineer can now call up during testing and see computed aerodynamic coefficients from any of eight different semi-empirical programs for missile configurations. This sometimes helps in assessing the need for other test data, the validity of data being collected, or configuration changes that should be investigated. It is hoped that this capability can be extended to encompass more general configurations.

Integrated, interactive test condition control is illustrated by the captive aircraft departure system test capability in the propulsion wind tunnel at the AEDC, for which interactive computation is essential. Using the technique, an unpowered aircraft model in a wind tunnel provides the aerodynamic forces and moments, and a propulsion system mathematical model provides computed engine thrust. These values are input to a computer program, *ie* the aircraft mathematical model (equations of motion), and the aircraft motion is computed. Tunnel Mach number and aircraft attitude, thus determined, are adjusted in the wind tunnel automatically. In this manner the response of the aircraft to given inputs is mapped.

2.6 Captive trajectory or two-sting testing at ONERA, ARA, and AEDC (Contributions 5-7)

Although all contributors to the discussion of this topic agreed that the 'trajectory' technique, dependent on an interactive computer, is far more efficient, a number of workers expressed support for the 'grid' technique because of the data bank it produces for parametric study. The cost of captive trajectory systems (CTS) or two-sting rigs (TSR) also is a consideration, and the cost/benefit ratio undoubtedly depends on the amount of stores testing that a particular organisation has to do. The following comparison was given by X. Bouis, of ONERA.

Trajectory	Grid
+ Short test duration.	- Long test duration and risk of missing a part of (x,y,z,ψ,θ,ϕ) field reached by the stores.
+ Good accuracy.	- Accuracy limited by interpolation mesh.
- No data recovery if there is a mistake in the trajectory parameters.	+ Off-line computations allowing parametric studies (and human mistakes!)
+ Saving wind-tunnel time by direct selection of the best configurations.	

Aside from the question of which mode is preferable, and related discussion of objectives, there is no disagreement about efficiency in deriving a given trajectory. M. Bouis mentioned 7 minutes for a CTS trajectory determination versus 3 hours for the same result using the grid testing mode. France, Great Britain, and the United States have wind tunnel laboratories making use of the CTS or TSR technique (TSR is the usual British designation).

2.7 Goals and plans

The general goals motivating integration of interactive, real-time computation with test units are improved economy, safety, and accuracy in obtaining information for the design of aerospace systems. The cost/benefit picture often is favourable because of rising cost of test unit operation and the declining relative cost and growing power of computer systems. Therefore interest in this activity will remain strong. Goals and corresponding plans are dependent on the circumstances at individual laboratories, so that the only AGARD activity that seems warranted is, perhaps, another cycle of Conveners' meetings in about two years' time. The rate of progress in this area should make it worthwhile to exchange information again after that interval. The first cycle has resulted in identification of representative technical activities and sites where the work is underway. This will aid in focussing attention and facilitate communication.

3 THE USE OF CFD TO CORRECT WIND-TUNNEL DATA

This section concerns the use of CFD to correct wind-tunnel data, and to show how to extrapolate the information to full-scale Reynolds numbers. The notes setting up the Group proposed that the Conveners should make an assessment of the potential benefits of replacing the current procedures for the correction of wind-tunnel results, and for their extrapolation from tunnel to flight Reynolds numbers, by CFD routines. The adaptive wall technique was specifically barred from the Group's discussions. The Conveners took this to include adaptive walls obtained by using either a flexible membrane or suction and/or blowing to generate an effective free air boundary.

3.1 Reports on work underway

The contributions presented at the Conveners' Group meetings (13-19) covered aircraft configurations from high lift at low speed to cruise conditions with transonic flow and tended to concentrate on the correct simulation of tunnel wall effects.

3.2 Extrapolation from tunnel to flight

No established methods for extrapolation of wind-tunnel test results to full-scale Reynolds numbers using CFD were reported. It was considered, in fact, that even corrections for wind-tunnel wall effects at a given flow condition are difficult to obtain with sufficient accuracy, particularly so if separated flow occurs in the wind-tunnel tests. Even for attached flow it is still difficult to obtain measurements of drag to the required accuracy. Thus, although it has been proposed that CFD codes could be used as a means of extrapolating results to full-scale conditions, it can be argued that this course of action is unlikely to be wholly satisfactory unless we have really arrived at the point where CFD codes are accurate enough to replace wind-tunnel measurements. The Conveners' meetings firmly believed that the latter, in general, is not the case. It remains true nevertheless that, in the absence of tests at full scale Reynolds numbers, CFD is potentially the most reliable means of bridging the gap between tunnel and flight. A possible improvement, at the present state of the art, is to make tests over a range of Reynolds numbers and then to extrapolate to full-scale conditions using CFD routines as a guide. This is feasible but suffers from the practical difficulty of making really comparable tests over a range of Reynolds numbers. All too often it is found that the type of flow changes over the range of Reynolds numbers being considered in a way not capable of being modelled by present CFD codes. The Conveners believe that, until CFD codes are very much more advanced, there will be no really satisfactory substitute for testing at the correct Reynolds number level. Limited extrapolation is now possible and acceptable where the flow is well behaved and fixed in character and, despite the problems involved, more extensive extrapolation will continue to be needed for transonic flows until new facilities are available which can give results closer to full-scale conditions.

3.3 Correction for wall interference (Contributions 13-18)

A number of the papers presented at the Conveners' Group meetings (Contributions 13-15) favoured measurement of the pressure distribution at the walls of the tunnel as the most accurate way of calculating tunnel interference effects both for high-lift low-speed conditions and at high subsonic speeds. Hackett, *et al.* suggested that, after many years of relatively slow progress, new advances are being made which promise to bring production testing out of the 'horse and buggy' stage and change the present small model, small correction philosophy. Even so, the flow must be 'correctable' in the sense that it is free from large flow curvature and other non-linear effects. The new advances are made possible chiefly by recent increases in computer power and reductions in computation costs. The essential point is that, from measurements of wall pressure signatures, it is possible to calculate the interference effects at the model location. Methods based on this concept are most promising for closed walled tunnels. For facilities using porous or slotted walls, detailed information on the flow conditions at the walls is exceedingly difficult to obtain so that, to make the problem manageable, conditions, including flow direction, have to be measured at some distance from the walls. It may therefore be preferable to continue to use more conventional correction methods in these cases although, as Lee, *et al.* and

Freestone show, the boundary condition at slotted or perforated walls can only be obtained from experimental investigations, and its form remains in some considerable doubt. Whichever method is adopted it is important to generate flows that are correctable in the sense that flow curvature corrections are small in the region of the model.

Lee, *et al.* also showed that panel methods can be very useful to account for interference effects such as mounting interference, etc.

3.4 Matching constrained and free-air calculations (Contribution 19)

Carr and Morrison have considered a novel approach to the problem of the testing of aerofoils at high subsonic speeds where supersonic flow may exist locally. The concept is to find, using CFD flow field methods, the equivalent free-air incidence and Mach number. The method relies upon being able to find for inviscid flow an aerofoil shape which generates the same pressure distribution, in the region of the tunnel walls and over the aerofoil surface, as that measured. The same calculation method is then used again for the calculated aerofoil shape, this time for free-air conditions, and the pressure distribution determined. Changes are then made to Mach number and incidence for the free-air case until the calculated aerofoil pressure distribution matches as closely as possible that in the confined flow calculation. If the differences remaining are significant then the flow is said not to be correctable, otherwise the incidence and Mach numbers obtained are the ones for the free-air conditions equivalent to the wind-tunnel test. The method is in the early stages of development and will be applied first to attached two-dimensional flows. If successful, there is some prospect that it could be extended to separated and to three-dimensional flows.

3.5 Goals and plans

It appears that some progress is being made in using CFD routines in the correction of wind-tunnel data, and that new methods are appearing as a result of the continuing improvements in the power and cost of computers. There remains the problem of deciding whether a flow is correctable, and this interacts with the type of walls used in tunnels. At high subsonic speeds the simpler boundary condition in a tunnel with solid walls permits reliable corrections, based on measured wall pressure signatures, provided the induced flow curvature remains small; on the other hand, a porous wall can be tuned to reduce the flow curvature problem but at the expense of more difficulty in determining the boundary conditions. It does appear that wind-tunnel testing should include measurements of the wall boundary conditions as a standard practice, and that corrections for tunnel wall interference should become routine throughout the main wind-tunnel centres. It is also recommended that calculations should be done for tunnel flows to see if measurements are likely to be correctable before a model is manufactured. Consideration should be given to using the pressure signature method (requiring now the measurement of flow direction as well as pressure) for tunnels with slotted and porous walls for high speed flows.

Wind tunnels which are to be used for the determination of Reynolds number effects should be calibrated for different unit Reynolds numbers and corrections made.

4 THE ROLE OF WIND-TUNNEL TESTING IN THE ASSESSMENT OF CFD CODES

This section is concerned with the critical assessment of CFD codes and considers the fluid dynamic modelling built into them. The section is not concerned with the development of CFD *per se*, but with the ability of CFD codes to represent real flows.

The rapid development of CFD has resulted in quite spectacular improvements in the ability to make realistic predictions of the flow over aerospace vehicles, but this has meant that limitations in the understanding of the physics involved have become more important, and in some cases lack of experimental evidence is now the main limitation. It is being found increasingly that CFD codes which are to be tested must first be applied in the design of experiments used to test them, so that the limitations of the method are taken into account and data are obtained under appropriate conditions. If this is not done the methods developed can be misleading when the modelling of the physics is stretched, perhaps unwittingly, beyond its range of applicability.

4.1 Reports on work underway

Several contributions (20-24) given at the Conveners' Group meeting stress the need for specialised and sometimes expensive experiments in support of CFD codes. It was accepted at the Eastern Atlantic meeting that, in any future tests on the overall flow over aerofoils and wings, the recommendations of Winter and Ohman in Ref 2 should be adhered to, as far as possible, if the main intention is to make adequate checks on CFD codes.

4.2 Recommendations of Winter and Ohman (Report of AGARD FDP WG 04)

It was recommended by Winter and Ohman that a datum experiment should be undertaken for a two-dimensional aerofoil in which the following measurements are made:

(1) The boundary conditions for the inviscid flow in the vicinity of the roof and floor;

(2) upstream and downstream boundary conditions;

(3) determination of sidewall boundary-layer thickness for at least two values of the thickness, changed for instance by applying suction;

(4) flow disturbance level including identification of acoustic and vorticity contributions;

(5) aerofoil pressure distribution and its spanwise variation;

(6) drag by wake traverse and its spanwise variation;

(7) boundary-layer development;

(8) wake development near the trailing edge;

(9) determination of the aeroelastic deformation of the aerofoil.

Some of the above measurements were thought to be less essential in experiments in which the ratio of tunnel height to model chord and the model aspect ratio are both sufficiently large for the interference effects to be small. The authors also recommend that the aerofoil should be of advanced design, and the test conditions should include a case with wholly subcritical flow, as well as a case with supercritical flow and a strong shock wave. Measurements of this kind are already being undertaken in Europe using the CAST 7 aerofoil, and using several wind tunnels.

Winter and Ohman also proposed a datum test series for three-dimensional wings. Their recommendations are for detailed measurements to be made for two test series which include both a high aspect ratio wing-body combination, with about 30 degrees sweep, and a low aspect ratio example with a more highly tapered planform and 45 degrees sweep. In each case the models should have sections of supercritical type with aft loading and, if possible, should exhibit a three-shock pattern in the flow on the upper surface, this being a severe test of calculation methods. It was also recommended that either the model should be tested in a minimum interference environment or else the boundary conditions should be measured in the vicinity of all four walls. The measurement of boundary conditions near the walls was considered to be a difficult task and perhaps only really possible for a closed wall tunnel.

4.3 Current and proposed test programs (Contributions 20-24)

The aim in the above recommendations is to reduce the scope for uncertainty about the measured flow to an absolute minimum, so that the data provide a reliable means of showing up deficiencies in the complete CFD method. These experiments are considered by Marvin to be of the *verification* type (Contribution 20).

Tests have recently been made of this type, using the DFVLR F4 wing-body combination in several European wind tunnels. This wing has a leading edge sweep of 27.1 degrees, an aspect ratio of 9.5, a taper ratio of 0.3, with a streamwise thickness:chord ratio of about 12%. The sections are of supercritical type with aft loading and the boundary layers are close to separation on both the upper and lower surfaces at the design point. There are also tests of the verification type on low aspect ratio wings being undertaken in USA at NASA Ames, in cooperation with McDonnell Douglas and Lockheed Georgia, and in UK at RAE Farnborough, where boundary-layer flow measurements will be made in addition to the surface pressure measurements required in the above recommendations. These tests are more advanced than the ones recommended in Ref 2, but are thought to be essential if we are to test adequately the CFD methods now becoming available; they should serve very well as test cases and go a long way to providing the data Winter and Ohman considered to be needed.

In addition to tests of the verification type there is a need for experiments of the *building block* type as suggested by Marvin. Here the need is to provide experiments which probe the physics of the flow and give an understanding of the modelling required for CFD. There are two types of experiments: (a) those required to support progress in turbulence modelling aimed at improved solutions of the Navier-Stokes equations with time-averaged values for the Reynolds stresses; and (b) those aimed at improvements to present methods which rely on matching together solutions for the inviscid outer flow and the viscous shear layers. Clearly, some of the evidence obtained from experiments aimed at (a) can be used for (b), and *vice versa*. Experiments needed to support this building block approach are numerous; some were listed by Marvin in Contribution 20 and others were listed at the Eastern Atlantic meeting. It is suggested that they need to be well documented experiments in which full details of the flow field, including the main Reynolds stresses, are measured. It is important that, where possible, the experiments are at Mach numbers and Reynolds numbers representative of flight, but they need contain only the feature under investigation as long as boundary conditions can be defined adequately. In the building block approach it is usually necessary to build a comparison CFD code into which empirical relationships, obtained from the measurements, are fed. This then results in the development of a suitable relationship which can be built, tested and used in a more general CFD code.

The experiments required for the building block approach can be split into four main types of flow: (a) attached flows; (b) separated flows with reattachment; (c) trailing-edge flows and wakes; (d) vortex flows. It is necessary to define and isolate the problem areas and set up experiments in which adequate measurements are made of the boundary conditions

as well as of the internal flow. Although a start has been made over the years in providing information of this type, particularly for attached flows, all too often insufficient information is obtained.

It is only in comparatively recent times that the aeronautical community has developed an interest in the turbulence models used in Navier-Stokes codes, since it is only recently that these codes have become applicable to problems of practical interest in aircraft design. At present the results of Navier-Stokes calculations for attached flows over aerofoils do not appear to be as reliable as results from the best methods using the matching codes, but Navier-Stokes methods appear to work reasonably well for separated flow and, in the longer term, are potentially superior in many respects. The main drawback is the excessive computing cost compared with results from comparable matching solutions. It is suggested by Peterson (Contribution 8) that computers with at least 40 times the power will be needed for comparable flow solutions. Although this level of computing power is unlikely to be available for some considerable time for use as a general tool, it is likely that solutions from Navier-Stokes codes will be used to improve the less advanced matching solutions.

One major advantage of the Reynolds-averaged Navier-Stokes codes is that it has already been shown that they can be used to predict unsteady phenomena, such as buffet caused by shock-induced separation and aileron buzz (Contribution 20).

4.4 Goals and plans

The general goal motivating the critical assessment of CFD codes is to be able to represent real flows over aerospace vehicles. It appears that experimental programs are in hand on both sides of the Atlantic with this common aim, and the development of a joint program would be advantageous, and economic. It is pleasing to report that cooperative programs which meet some of the objectives put forward in Ref 2 by AGARD FDP WG 04 are already in hand. A useful extension of this cooperation would be to make a start on a cooperative program for the building block approach. There is a need to define the experiments required, but those identified at the Eastern Atlantic meeting as needing to be considered in the immediate future are:

(a) Two-dimensional flows

Interacting wakes, and boundary layers; base flows for aerofoils; shock-wave/boundary-layer interactions; trailing-edge flows.

(b) Three-dimensional flows

Flows in wing/body junctions; swept shock-wave/boundary-layer interactions; vortex flows; swept base flows for wings.

(c) Unsteady flows

Although no specific flows were identified, it was thought to be important to make some measurements in this domain, especially as the Reynolds-averaged Navier-Stokes codes appear to be able to deal with some unsteady flows.

It appears that this subject would benefit from further discussions, either by the Conveners' Group or on an *ad hoc* basis, with a view to assessing the possibilities for a cooperative program.

5 USE OF CFD AS A GUIDE DURING TESTING AND THE POSSIBILITIES FOR INTERACTIVE CFD

The present, limited use of near real-time computed solutions or stored data and solutions for guiding wind-tunnel tests at the AEDC is mentioned earlier in this report. That may be viewed as the state of the art and a step toward future use of computational fluid dynamics (CFD) for the same purpose. As explained earlier, CFD is here defined as numerical solutions of the equations of fluid flow, as distinct from more empirical treatments.

At this time, the only generally feasible mode of using CFD as a guide during testing is to do the computation prior to the test and simply call up the results when needed. To do more would require a dedicated Class 6 computer system and extensive preparations. Even then, the speed with which data are generated, once the test is underway, would make it inefficient to try to carry out more than a few CFD solutions for use in guiding the ongoing test. It would also be necessary to provide the engineers with good tools for selecting and viewing only the computed results desired for study. It must not be necessary for the engineer to be a CFD specialist.

5.1 Reports on work underway

Contributions 8-12 relate to this part of the discussion.

Following are brief comments based largely on those reports.

5.2 The NASA Numerical Aerodynamic Simulator, NAS (Contribution 8)

Even though the NAS is in the planning and design stage, its implications in regard to CFD made it an interesting topic. In the years following the advent of the NAS, the improved CFD codes that will result from its use and the increased power of commercially

available computers that will benefit from its pioneering development will affect the future of CFD as a supplement to testing. The extensive study conducted in order to justify the NAS has helped to define the future role of CFD, as well as define required computer system specifications.

Figs 1 and 2 were a part of Victor Peterson's presentation at the Conveners' meeting in the US. The first figure summarises the stages of development of CFD and relates advances to the class of computer system which makes it feasible to obtain solutions in the order of minutes. The second figure briefly summarises NAS project planning.

5.3 Lower-cost computers for CFD (Contribution 9)

For the same reasons given for reviewing the NAS project, an assessment of the announced capabilities of less expensive computer systems is of interest. Hardware that offers impressive capability for the order of $1 million may be assembled by combining a current 'midi' computer with an array processor. It was stated that a dedicated computer of this type could provide three-dimensional inviscid, or two-dimensional viscous flow solutions in times suitable for comparison with tunnel results.

5.4 CFD now practised (Contributions 5, 8, 10-12)

An appreciation of the reasons for and ways in which CFD is now practised was gained from several of the presentations. Some of the types of computations particularly desirable for interactive or comparative purposes in conjunction with testing are listed below for illustration.

(1) Correcting data for wall and model support effects or flow angularity in wind tunnels;

(2) extrapolating data by computing viscous effects for different Reynolds numbers or wall temperature conditions;

(3) extrapolating data by computing real gas effects;

(4) predicting aeroelastic effects and correcting data;

(5) comparing data with calculations to support test unit calibration or increase confidence in test data;

(6) converting measured data to the desired, higher-order information by combining CFD with the experimental measurements.

The last type of work was represented by Contribution 12 which described a novel concept wherein a fast scan of momentum flux across a control volume using a laser velocimeter would be input to a CFD code for computing the flow field.

5.5 Goals and plans

The general goals in the CFD area are obvious, namely improved accuracy, speed, and scope of applicability. In the context of the Conveners' meetings, the goal is to supplement testing in ways which will improve efficiency, accuracy, and usefulness for design purposes. All major wind-tunnel laboratories have an active interest in the computational supplementation of testing, but the emphasis varies at this time. Many participants believed that near real-time CFD is not needed.

Considering the strong international efforts toward improved CFD and the growth in computational capability taking place, it does not appear that additional efforts towards those ends are required of the groups interested in integration of computers and wind tunnels. Continued watch for opportune applications and long-range planning to take advantage of CFD progress will be facilitated by meetings of the type being described.

6 CONCLUSIONS AND RECOMMENDATIONS

The integration of computers and wind-tunnel testing is a topic which has progressed naturally with the increasing availability of fast computers. It is obvious that on-line, interactive use of computers for data processing and test systems control has led to improvements in speed, accuracy, and economy. It has also made new test techniques feasible and enabled advances in the scope or type of experimental data that can be obtained in laboratory facilities. The frequent interchange of information on developments in this area is going to help all participating laboratories to make the best use of computers for their particular needs and resources. The Conveners' meeting made it clear that all organisations do not want to pursue the same plans for integration of computers and test units. Different requirements exist and different solutions are appropriate, so joint programs are not generally necessary, or desirable.

The use of CFD to correct wind-tunnel data represents a further improvement in the quality of simulation by the more accurate compensation for wall effects and support interference. Both in the study of wall corrections and in experiments to assess CFD codes there are opportunities for helpful joint programs to be organised. The Conveners' meetings strongly emphasised the need for completeness in measurements of the relevant flow conditions in work of this type, and for a critical approach to the evaluation of results. Considering that wall corrections, transonic working sections, and adaptable walls

are closely allied subjects, the Conveners do not suggest joint programs separate from those being conducted by working groups already concentrating on this specific problem.

Experiments planned to test CFD codes should be designed with the sensitive aspects of the code in mind as well as the coverage of all relevant flow conditions in the measurements. A number of programs for the comparison of calculated and experimental results are underway and periodic meetings for discussing results are expected. However, the CFD community may not create the kind of interchange or joint planning that can be accomplished by AGARD, and there is a need to review this program of work in the light of recent improved performance of CFD codes, and the introduction of the Class 6 machines into regular use. Lack of experimental evidence is likely to be one of the main limitations in being able to use Reynolds-averaged Navier-Stokes codes. Some cooperative projects for the purpose of assessing CFD codes are already underway and the desirability of broadening them should be considered. Suggestions to that end are given earlier in this report.

Use of CFD as a guide during testing, and advanced interactive uses, will grow naturally as skill in computational techniques and power of available computers grows. Therefore, it seems that emphasis in joint activities will be better placed on programs that advance CFD, including experiments for assessment of results and improvement. The degree and methods of integration with wind-tunnel testing probably will develop according to the needs of individual laboratories.

There is ample evidence that integration of computers and wind-tunnel testing has already proved advantageous. Although it will be several years before on-line CFD truly supplements wind-tunnel testing and a longer period before CFD supplants a major amount of tunnel work, the various uses for CFD in connection with wind-tunnel testing were described in the meetings and in this report. The complementary roles of CFD and testing are the important features of this discussion and should guide planning at the present time.

REFERENCES

1 J.L. Kerrebrock, *et al.*: "The MIT blowdown compressor facility." J. of Eng. for Power, Vol.46, No.4, October 1974

2 "Experimental data base for computer program assessment." Report of the Fluid Dynamics Panel Working Group 04; AGARD Advisory Report 138, 1979

ANNEX

CONTRIBUTIONS PRESENTED AT CONVENERS' MEETINGS

1 Interactions between computer modelling and testing of propulsion systems.
W.F. Kimzey
AEDC, Tullahoma, USA

2 Computer aided data collection and reduction in a blowdown compressor facility.
E. Epstein
Massachusetts Institute of Technology, USA

3 A computer controlled system for acquisition and interactive analysis of unsteady aerodynamic data.
J.P. Heaman
NASA Marshall Space Flight Center, USA

4 Interactive graphics access to semi-empirical aerodynamic coefficient prediction programs for analysis of missile wind tunnel data.
W.B. Baker
AEDC, Tullahoma, USA

5 The role of computational fluid dynamics in wind tunnel testing.
D.L. Whitfield
AEDC, Tullahoma, USA

6 The ONERA captive trajectory system and the enormous amount of information which has to be processed in modern dynamic facilities.
X. Bouis
ONERA, Modane, France

7 The Two-Sting Rig (TSR) system for captive trajectory testing at ARA Ltd.
D. Morton, K.J.C. Eyers
Aircraft Research Association, Bedford, UK

8 Interaction of computers and wind tunnels and the numerical aerodynamic simulator.
V.L. Peterson
NASA Ames Research Center, USA

9 Computers for interactive wind tunnel testing.
T.D. Taylor
The Johns Hopkins University, USA

10 Use of CFD for wind tunnel data improvement.
W. Schmidt
Dornier GmbH, Friedrichshafen, Germany

11 CFD evaluation of flexible wing data obtained in the AEDC 16T transonic wind tunnel.
R.C. Bauer, D.E. Wieduwilt
AEDC, Tullahoma, USA

12 A simple integrated laser/computational method for flow field and force determination in wind tunnel testing.
J.M. Wu, H.P. Chou
University of Tennessee Space Institute, Tullahoma, USA

13 A review of the wall pressure signature and other tunnel constraint correction methods for high angle-of-attack tests.
J.E. Hackett, D.J. Wilsden, W.A. Stevens
Lockheed, Georgia, USA

14 Numerical simulation of wall and model support interferences in wind tunnel testing.
K. Lee, A.J. Krynytzky, N. Zinserling, E.G. Hill
Boeing Aircraft Company, Seattle, USA

15 Techniques developed in Europe for tunnel wall corrections using measured boundary conditions.
P.R. Ashill, D.J. Weeks
RAE Bedford, UK

16 The use of computational fluid dynamics for wall interference in transonic flow.
A. Eberle
MBB Munich, Germany

17 Reynolds number effects on wind-tunnel wall boundary layer and influence on shock position.
A.F. Aulehla
MBB Munich, Germany

ANNEX (concluded)

18 Incorporation of viscous effects.
M.M. Freestone, P. Henington
City University, London, UK

19 Use of flow field methods to calculate wind tunnel corrections for two-dimensional data in supercritical flow.
M.P. Carr, J.I. Morrison
Aircraft Research Association, Bedford, UK

20 Advancing computational aerodynamics through wind tunnel experimentation.
J.G. Marvin
NASA Ames Research Center, USA

21 Simple experiments to assess CFD codes.
L. Squire
Cambridge University Engineering Laboratory, UK

22 The need for experiments to provide bench-mark test data - activities at ONERA.
J.J. Thibert
ONERA, Chatillon, France

23 An investigation into the viscous effects on a family of advanced aerofoils of 14% thickness.
D.J. Weeks, P.R. Ashill
RAE Bedford, UK

24 Measured and predicted oscillatory flows on a 14% thick biconvex wing transonic speeds.
D. Mabey, B.L. Welsh, B. Cripps
RAE Bedford, UK

Approximation level	Capability	Pacing items	Computer class (3-D applications)
Linearized inviscid	Subsonic/supersonic • Pressures • Vortex and wave drag	None	CDC 6600 CDC 7600
Non-linear inviscid	Above plus: • Transonic • Hypersonic	Grid generation for complex geometries	Illiac IV Cray 1S Cyber 205 Burroughs BSP
Reynolds-averaged Navier-Stokes	Above plus: • Total drag • Performance boundaries (*eg* stall/buffet/ flutter)	• Advanced computers • Improved turbulence models	At least 40 times current super-computers
Turbulent eddy simulation	Above plus: • Aerodynamic noise • Structure of turbulence	• Advanced computers • Improved subgrid-scale turbulence models	At least 1000 times above capability

Fig 1 Stages of development of computational aerodynamics

- OBJECTIVE:

  Develop a facility for use by NASA, DOD, Universities and Industry to:

  - Complement wind tunnels in the aerodynamic design process
  - Provide a tool for advanced fluid dynamic research

- REQUIREMENTS:

  - Speed - at least 1 billion arithmetic operations per second
  - Memory - at least 40 million directly addressable words
    - at least 200 million block addressable words
  - Development risk - low (use proven memory and logic technology)
  - Usability - easy to program

- DESIGN PHILOSOPHY:

  - Optimize for fluid dynamic applications but require performance comparable to general purpose machines for other scientific disciplines

Fig 2 Numerical aerodynamic simulator (NAS)

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14. Abstract

The Advisory Report includes the results of six meetings sponsored by the Fluid Dynamics Panel and conclusions drawn from the reports prepared by the meeting chairmen. In each of the three subject areas, meetings were convened in the US and Europe, with the results being combined by the chairmen. Applications of the technology discussed in this report can afford large improvements in windtunnel capability and effectiveness.

This Advisory Report was prepared for the Fluid Dynamics Panel of AGARD.

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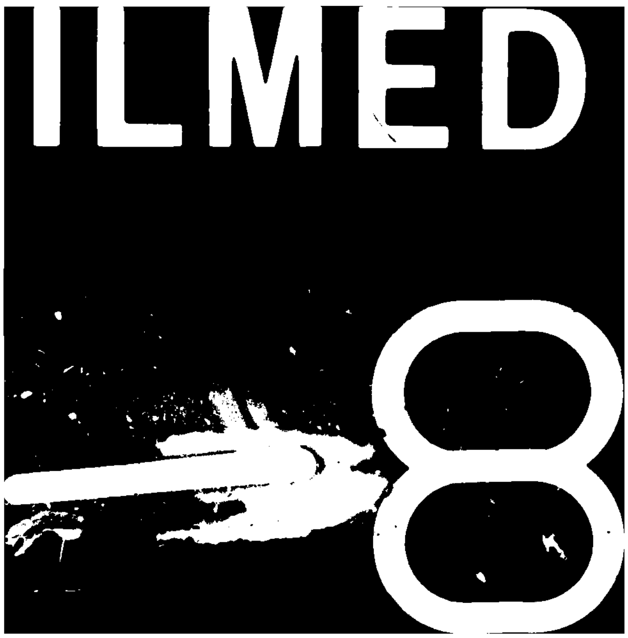
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